Subcontractor Report

August 2000 • NREL/SR-500-27475

Near-Term Research and Testing of the CWE-300

Executive Summary of Project Final Report September 1, 1997–August 30, 1999

Cannon Wind Eagle Corporation
Bakersfield, California

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

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Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

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NREL Technical Monitor: Alan Laxson

Prepared under Subcontract No. ZAT-7-16477-03

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1.0 INTRODUCTION AND ACKNOWLEDGMENTS

This Executive Summary was submitted to the National Renewable Energy Laboratory (NREL) by the Cannon Wind Eagle Corporation (Cannon). The report is submitted as part of NREL subcontract ZAT-7-16477-03 titled "Near-Term Research and Testing" (NTRT). This cost-shared contract encompassed the further engineering, component tests, system field tests, certification and preparation for manufacture of the existing Cannon Wind Eagle 300 kilowatt (kW) (CWE-300) wind turbine. The contract was initiated in late September 1997 with a planned 36-month period of performance.

Cannon was awarded a separate NREL subcontract for the development of a 25- or 30-kW version of the Wind Eagle architecture. This subcontract, part of the NREL Small Wind Turbine (SWT) Project, also was signed in September 1997. The SWT project used the analysis, modeling, and testing results flowing from the NTRT effort. Thus, the start of intensive effort on the SWT subcontract was delayed to utilize the NTRT results more efficiently.

As described below, subsequent, and unforeseen events led to the relinquishment of the SWT subcontract during the first half of 1998. These and other machine-related events led also to a reduction in scope of the NTRT subcontract and an early completion.

The substantial effort performed and results accomplished under the NTRT program (and under the SWT program during its short duration) reflect the expertise, energy, and commitment of a number of organizations and people. These include the field, engineering, and management personnel of Cannon, notably Fred Beasom, Phil Darling, Robert Ochoa, Sean Roberts, Donny Roe, and Jeff Wilks. The effort was aided by a number of support contractors to Cannon. These included Dynamic Design of Davis, California, in the persons of Kevin Jackson, Woody Stoddard and John Vandenbosche. OEM Development Corporation of Boston, Massachusetts, provided engineering, management and documentation support in the persons of Jamie Chapman, Daniela Gran, Ruth Marsh, and Deming Wan. Tim Olsen of Tim Olsen Consulting, Denver, Colorado, provided valuable engineering calculations and technical insight. Jay Carter Sr. provided valuable technical insights and experience during the initial part of the effort. Cannon project management was provided by Fred Beasom and Craig Loke. Jamie Chapman served as principal investigator.

Our acknowledgments would not be complete without listing the substantial assistance provided by the management and technical staff of the NWTC operated by NREL of Golden, Colorado. Alan Laxson, as project manager, provided reasoned and rational guidance during sometimes trying and difficult periods. Alan Wright, in his work with the ADAMS model of the Wind Eagle, showed the value and power of the modeling and analysis tools developed by NREL during the last several years. The painstaking and thorough experimental work contributed by Neil Kelley, Rich Osgood, and their colleagues was invaluable in validating and tuning the ADAMS model.

Finally, the initiation and continuation of the Cannon Wind Eagle effort is due to the vision of the principals of Cannon, Gerry Monkhouse, and Brian O'Sullivan.

1.1 The Cannon Wind Eagle Wind Turbine

The Cannon Wind Eagle 300 wind turbine is a lightweight, flexible machine with a number of innovative design features that, relative to comparable rigid-hub machines, promises to contribute to reduced capital, installation, and maintenance costs.

The architecture of the CWE-300 evolved from earlier wind turbine models developed during several decades by Jay Carter Sr. (Carter) and his son Jay Jr. The architecture and details of the CWE-300 were carried forward principally by Carter. The design retained many of the desirable features of earlier machines, addressed problems exhibited by those machines, and incorporated further innovative design features.

The CWE-300 design, as used in the NTRT program, incorporates the following features:

(1) A downwind, two-bladed, stall-controlled, 29 meter (96 foot) rotor consisting of a flexible, single-piece, flow-through, composite spar to which flexible, load-shedding, lightweight, composite blades are attached.

(2) A compact nacelle and mainframe that rotates not only in yaw but also in the tilt direction enabling enhanced load-shedding and increased energy capture for non-horizontal winds.

(3) Lightweight drivetrain construction that combines inexpensive materials with a light weight, two-stage, highly integrated planetary gearbox and conventional induction generator.

(4) A 49 meter (161 foot), guyed pole tower that incorporates provisions for rapid raising and lowering of the machine using a gin pole and winch, thus permitting maintenance at ground level.

(5) Low-cost foundation consisting of four concrete pads for the guy wires and one for the pole tower.

(6) Active nacelle-yaw orientation at low wind speeds with passive yaw damping or free yaw at high wind speeds.

(7) Hydraulically actuated, collective blade-pitch with two pitch positions (run and stop).

(8) Blade-pitch hydraulic system mounted in the rotating frame.

(9) Aerodynamically self-starting rotor.

(10) Rotor is aerodynamically stalled via a full-span, fail-safe spring mechanism. A slow blade-pitch rate is utilized for normal shutdown conditions, whereas a faster pitch rate is for critical high-speed shutdowns.

(11) Manually adjustable blade-pitch for optimum power production

(12) Generated electric power and the control and status signals are brought out using slip-rings.

The rotor incorporated an LS-1 airfoil over its initial 78 feet with the outboard section utilizing the Solar Energy Research Institute NREL S806A airfoil. Figure 1 is a photograph of a CWE-300 prototype (P2) installed for testing at Cannon facilities in Tehachapi, California. The principal components and nomenclature of the CWE-300 are illustrated in Figure 2.

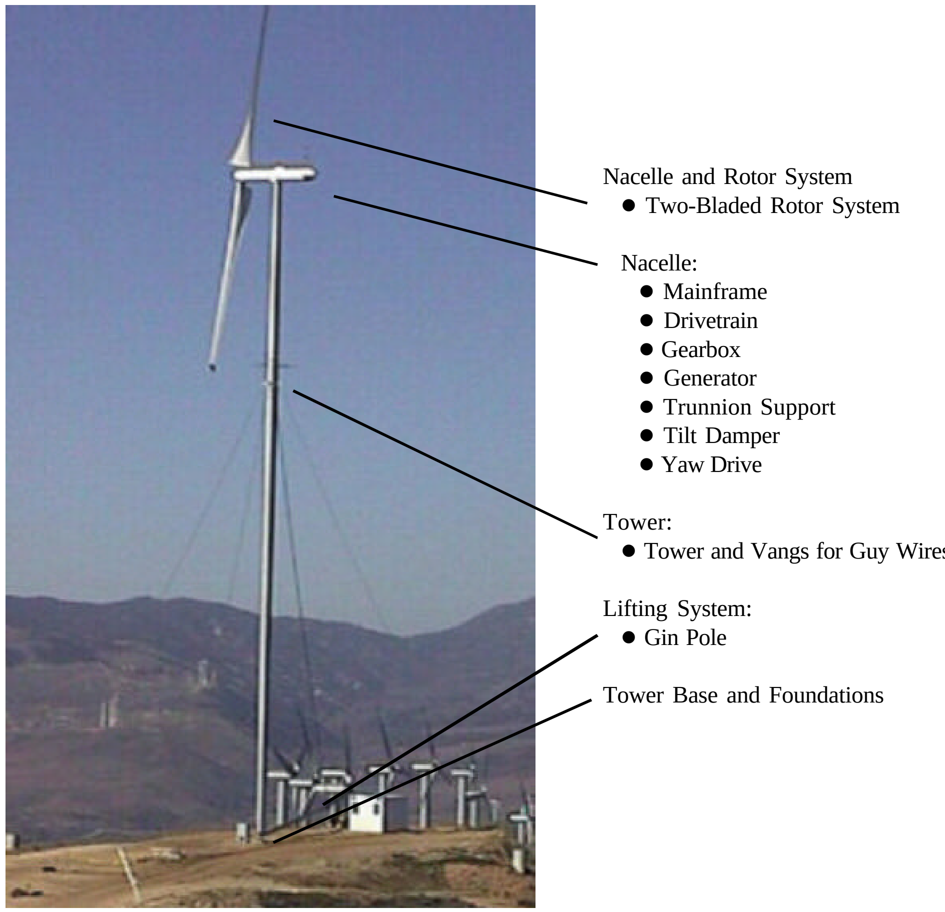

Figure 1. Photograph of the CWE-300 prototype P2 in Tehachapi

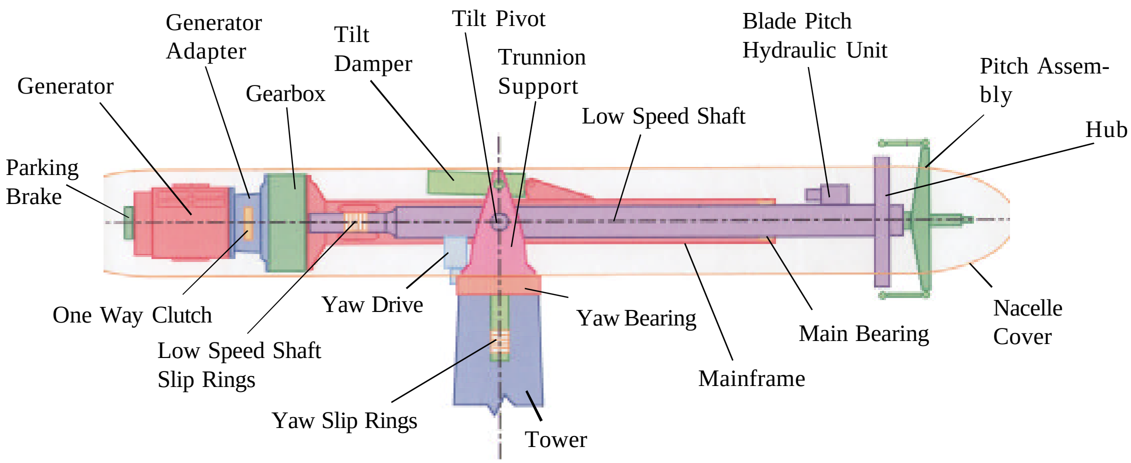

Figure 2. Principal components and nomenclature of the CWE-300 wind turbine

1.2 Evolution of the NTRT Program

At the onset of the NTRT subcontract, a considerable body of experience and information had been developed by Carter and Cannon. In addition to the experience gained during the past two decades with various lightweight, flexible turbines information on the CWE-300 included engineering drawings, component procurement data, and the experience gained through the construction and testing of a number of Wind Eagle prototypes.

The earliest Wind Eagle prototype was a 10 meter diameter, 25-kW machine. This was followed by several 300-kW prototypes, the first of which was constructed in 1988. For the Cannon and NTRT programs, early performance information was gained using a Wind Eagle prototype previously tested by Carter at a site in San Gorgonio Pass, California, and subsequently moved to Tehachapi for operational tests. This was the E1 prototype.

In testing at Cannon facilities prior to the onset of the NTRT subcontract, the E1 machine was tested with two different rotors. The first had a flexbeam spar precone of 6 degrees. The second utilized a spar with a 0-degree precone. The E1 mainframe and drivetrain were smaller than those of the later six preproduction prototypes, and used an 88 foot (26.8 meter) rotor diameter for both E1 tests.

Cannon also had constructed six preproduction prototypes designated as P1 through P6. All utilized 0-degree flexbeam spars. One of these machines the P1 was installed at NREL's National Wind Technology Center (NWTC) near Boulder, Colorado. A second machine the P2 (the NTRT precertification prototype) was provided under this subcontract for instrumentation and testing at the Cannon wind farm facilities in Tehachapi, California. Both the P1 and P2 machines had 96 foot (29.3 meters) diameter rotors and utilized a tower that resulted in a hub height of 161 feet (49 meters). Smaller diameter blade sets (88 feet diameter) also had been fabricated but were not used with either the P1 or P2 preproduction prototypes.

Because of operational problems (principally blade contacts with the tower) revealed in 1997 during tests of the E1 machine, the P2 machine was modified at Cannon facilities in Texas prior to its installation in October 1997 at Tehachapi. The modifications principally consisted of increasing the distance from the yaw axis to the hub, changes to the geometry and damping characteristics of the nacelle tilt damper, and changes to the control of the nacelle yaw damper. The P1 machine at the NWTC was not modified and remained essentially in its as-delivered configuration. The remaining machines, P3 through P6, reside in Cannon inventory in their original configurations.

The Wind Eagle architecture and technology were licensed to the Cannon Wind Eagle Corporation from the Wind Eagle Corporation, of which Jay Carter Sr. was a principal. The license agreement was signed in August 1995, prior to the involvement and participation of NREL. Further licensing negotiations between Cannon and the Carter group were initiated during the second half of 1997. The parties failed to reach agreement and the discussions were terminated in mid-March 1998. The Wind Eagle license to Cannon was withdrawn.

After termination of the Cannon license, NREL and Cannon mutually decided to restrict the scope of the NTRT effort and to focus on the operation, instrumentation, and testing of the P2 Tehachapi machine. The expectation was that the P2 data would complement measurements taken on the P1 machine at the NWTC. Both data sets were to be used with NREL and Cannon modeling efforts using the Automated Dynamic Analysis of Mechanical Systems (ADAMS), Fatigue, Aerodynamics, Structures, and Turbulences (FAST) and YAWDYN codes. At this time, the engineering team assembled for the NTRT and SWT efforts was significantly reduced in size.

As a result of this reduction the Cannon team decided to focus principally on the instrumentation and operational testing of the P2 machine. Shortly thereafter, the ADAMS P2 modeling effort undertaken at Cannon (through OEM Development Corporation) was suspended as a result of the modeling expert accepting other employment near the end of May. The parameterized P2 model (that built upon an ADAMS P1 model provided by NREL) was then transferred to NREL, after which the focus of the modeling effort shifted to NREL and the P1 machine.

During the period of instrumentation and operation of the P2 machine, the objectives of the Cannon Tehachapi effort were: (1) to accumulate, with minimal disruptions, grid-connected operational time so as to demonstrate the long-term viability of the machine and (2) to complete installation of the sensors, wiring, signal conditioning, and data acquisition systems for measurement of loads and other engineering parameters needed for model validation and design certification. Because these objectives were somewhat at odds, work-arounds were implemented. These involved installing instrumentation during times of low wind and during machine repair and maintenance intervals.

Through the end of April 1998, the P2 machine had accumulated 658 hours. After April, the machine no longer operated. The strain gage and other instrumentation, along with the recording channels were substantially complete by early July.

In July, at the direction of NREL, effort was focused on machine disassembly, inspection, documentation of program results, and subcontract completion.

Finally, although the Cannon Wind Eagle Corporation and its operations were not included, the Cannon Energy Corporation wind farm assets and the associated operations and maintenance organization in Tehachapi were sold in September 1998.

1.3 Wind Eagle Performance Successes and Problems

Valuable insights into the performance characteristics of the Wind Eagle design were gained from the E1 and P2 tests in Tehachapi. Surmountable problems occurred with the E1 and P2 prototype turbines during their testing operation in Tehachapi because of installation and extreme wind conditions. Some blade cracks in noncritical areas resulted from handling during installation. Others appear to be associated with blade coning during high-wind shutdowns. The hydraulic fluid used in the blade-pitch system exhibited significant viscosity changes throughout the full range of operating temperatures, leading to variability in the pump efficiency and blade-pitch rate from stall to run position. Premature wear patterns in hub components and structural cracks associated primarily with the nacelle tilt damper were apparent after test operation of P2. In addition, the nacelle tilt damper of P2 may not have had the required air space in the hydraulic cylinder for appropriate damping.

In operation, the machine exhibited such anomalies as the tendency to occasionally yaw upwind during start-up and during low-wind, grid-connected operation. Yaw and power excursions were evident during start-up. Some of these anomalies may have been caused by the turbulence from other wind turbines situated upwind. Because of blade flexibility and the lack of adequate fixturing, the blade-pitch angles were difficult to adjust accurately and repeatably. Thus differences in pitch between the opposing blades may also have been a contributing factor. The grid-connection procedures were not able to be tested and analyzed for proper operation concerning generator synchronization and connection. This may have had an adverse effect as well.

On the other hand, there were no significant problems with the hub, flexbeam spar, mainframe, gearbox, generator, and other drivetrain components of either machine. Further, measurements on the E1 machine indicated that blade root-flap bending moments were reduced significantly compared to the loads representative of a comparable rigid-hub machine. Comparison of measured E1 blade root-flap moments with those from a rigid-hub Nedwind turbine indicated that a 75% to 80% reduction in loads was realized in the Wind Eagle rotor configuration.

The principal and most serious problems displayed by the E1 machine were blade-to-tower strikes. During the closing months of 1997, the E1 machine experienced three tower strikes, each of increasing severity. These occurred during power generation or a high-speed shutdown procedure. The gyroscopic moments associated with a gust-induced, rapid-yaw motion have been identified as the most likely cause of these strikes. As mentioned, the E1 test machine was fitted with an 88 foot rotor. Since the E1 nacelle length was designed to use a 78 foot rotor with 6-deg pre-cone, the use of an 88 foot rotor with 0-deg pre-cone significantly reduced the blade tip clearance. The original E1 configuration did not experience any tower strikes during its test operation in San Gorgonio or Tehachapi. Concern for tower strikes prompted the modification of the original P2 configuration to substantially increase the nominal rotor clearance. This was done mainly by increasing the nacelle length. Other remedies also are possible but were not able to be tested. These are discussed in the next section.

1.4 Tower Strike Remedies

A number of remedies were developed to minimize the probability of tower strikes. Some were implemented as modifications to the P2 machine prior to its installation. Others were to be evaluated using the ADAMS model of P2. Unfortunately, the program was redirected before meaningful results were obtained from the ADAMS model of the modified P2 machine. However, modeling of the P1 machine by NREL yielded valuable insights. Some of the results of the P1 modeling by NREL are given in Wright (1998a and 1998b).

The goal for the tower strike problem was to reduce the probability of a strike to nearly zero during the projected 30-year operational life of the machine. This was to be demonstrated through the P2 by measuring the blade-to-tower clearance distance during every blade passage, using optical or acoustic sensors with time interval measurements converted to distance of closes approach. The statistics of these measurements, correlated with wind conditions and machine state, were to be used to assess the probability of a tower strike over longer periods of time.

Possible remedies for reducing tower strikes include the following (1 through 5 were implemented on P2):

(1) Increasing the distance from the yaw-axis to the hub by increasing the length of the drivetrain and main frame.

(2) Improving the geometry of the nacelle tilt damper.

(3) Increasing the damping of the nacelle tilt damper.

(4) Limiting the angular extent of the hub-tilt (rotor-down).

(5) Limiting the nacelle yaw rate during startup and at low wind speeds.

(6) Changing the precone of the flexbeam spar from the 0-deg value used in P2 to a larger value. An earlier E1 test rotor had a spar precone value of 6 degrees, whereas the three-bladed, 600-kW MS4 of the United Kingdom Wind Energy Group had a rotor precone of 7 to 8 degrees.

(7) Incorporation into the mainframe of a few degrees of nacelle hub tilt-up with the nacelle axis offset by a few inches from the yaw-axis. The MS4 incorporated 5 degrees and 2 feet.

(8) Design and fabrication of the rotor to incorporate asymmetrical stiffness, that is, to have the blade be less flexible as it moves toward the tower than in the direction downwind and away from the tower.

1.5 Remedies Implemented in the P2 Machine

The first five of these remedies were implemented in the P2 prototype test machine. All were to be modeled using ADAMS and FAST. Relative to the as-built configuration of the six preproduction prototypes, the overall length of the P2 machine was extended by 7 feet. This increased the original 11 foot distance from the yaw-axis to the hub by 4 feet.

The geometry of the nacelle tilt damper mounting brackets was changed to reduce the stresses experienced by the brackets and to give a slightly increased range of damper travel. The damping rate was increased.

The initial angular range of the nacelle tilt damper was –5-deg (hub down and blades toward the tower) to +5-deg (hub up and blades away from the tower). By redistributing the rubber washers used as semisoft stops to limit the range of motion, the tilt damper angular range was changed to –3-deg hub down and +5-deg hub up.

1.6 P2 Operational Results

The remedies implemented apparently had the desired effect of minimizing the probability of a tower strike. The P2 machine suffered no blade strikes during the period from mid-October 1997 through the latter part of April 1998. At the end of this period, the machine had accumulated 658 operational hours and had generated 99,000 kilowatt-hours of electricity. Further, because of the installation of simple blade-to-tower approach sensors, we know that the blade came no closer to the tower than 4 feet during P2 operation. The sensors were eight, breakable, 4 foot plastic rods (called porcupines) installed around the periphery of the tower at approximately the height of the blade tip passage location.

In addition, there were no significant problems with the gearbox, generator or other major drivetrain components.

2.0 SITE LAYOUT

The CWE-300 test site is located on a knoll, surrounded by the Cannon Energy Corporation wind farm (see Figure 3). In the prevailing wind direction (from the northwest), the terrain slopes down steeply and is unobstructed by other turbines. All other directions are obstructed by power-generating wind turbines.

As illustrated in Figure 4, the meteorological tower is located upwind from the P2 turbine tower, about 100 feet away, and about 53 feet downslope in the prevailing wind direction.

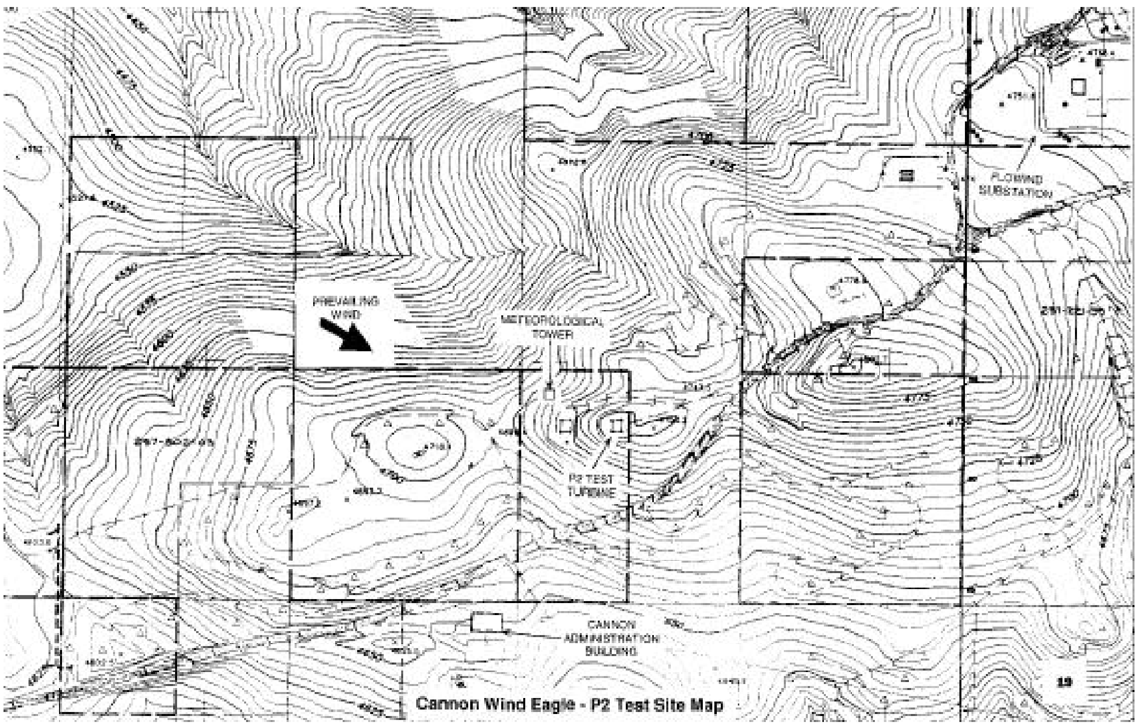

Figure 3. Topographical map of the P2 test site.

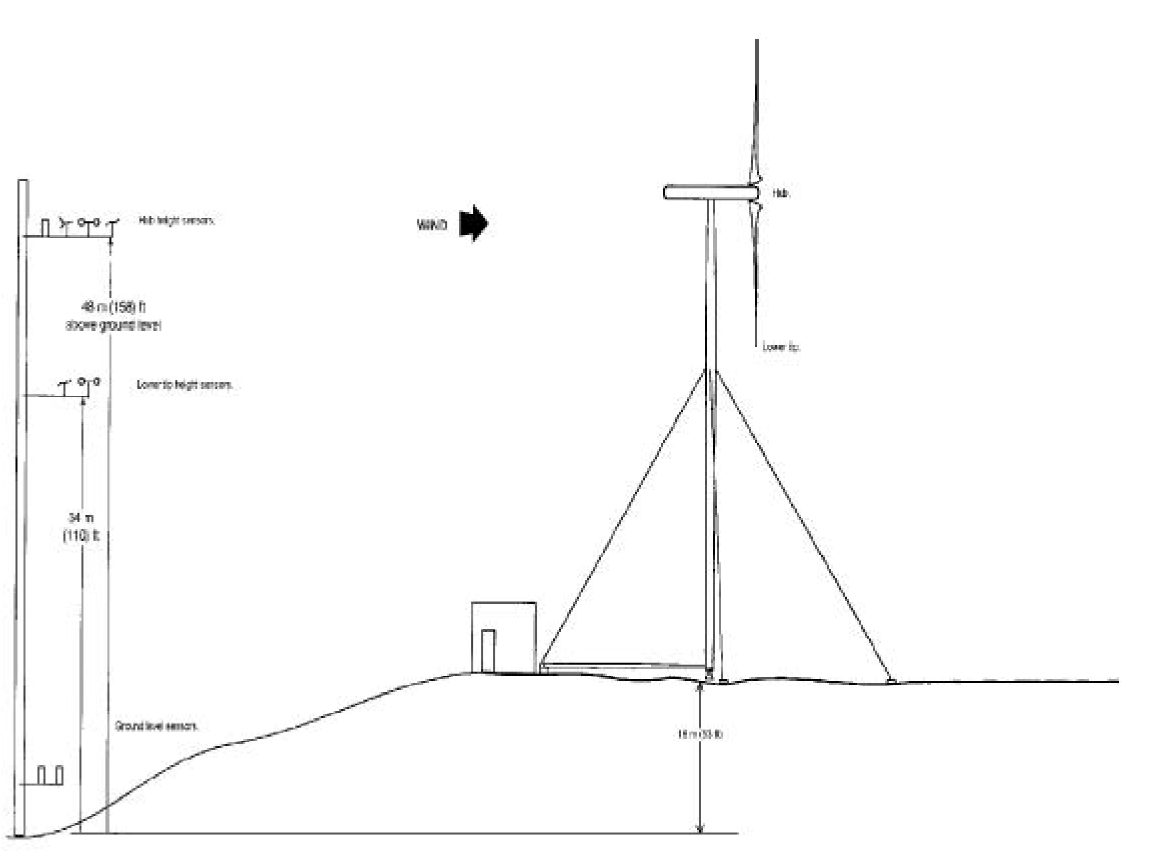

Figure 4. Drawing of meteorological tower and turbine

Figure 5. Image from the CWE-300 test site

The CWE-300, which was oriented east to west, is shown lying down. The image was taken looking westward.

3.0 DATA ACQUISITION SYSTEM

The Zond Advanced Data Acquistion System (ADAS) system was used to collect data from the sensors. All data acquisition system hardware was connected to the central processing computer located in the on-site control shed. This computer used an IBM-compatible personal computer.

The Data Acquisition Modules (DAMs) were mounted directly to the nacelle, tower, and meteorological (MET) tower. The DAMs were connected to each sensor. Each DAM had eight slots for different cards (e.g., digital, anemometer, or quadrature). Data filtering was handled automatically by the DAMs by installing the proper card in each DAM. The DAMs could hold 4 megabyte (MB)of data (regardless of the sample rate), which was stored until the download command was given by the central computer.

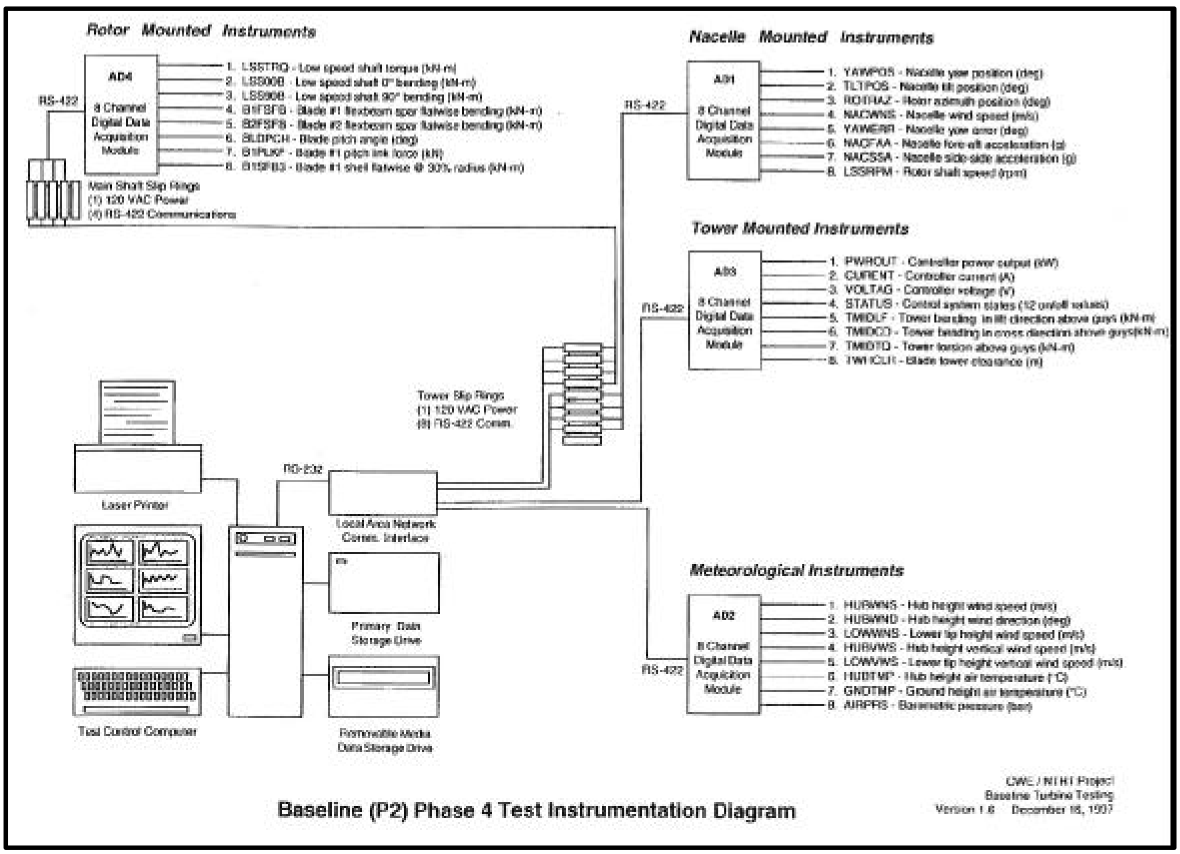

Figure 6. Phase 4 test instrumentation diagram

3.1 Data Matrix

The following tables describe the planned baseline test matrix. This test matrix was not fully implemented because of project termination.

Table 1. Phases 3 and 4 test matrixes

Baseline Turbine Testing - Phase 3 Test Matrix

Test Configuration	*Data Collection Goal*					*Relative Priority*				
	<4 m/s	4-8 m/s	8-12 m/s	12-16 m/s	>16 m/s	<4 m/s	4-8 m/s	8-12 m/s	12-16 m/s	>16 m/s
1 Normal Operation Engineering @ 40 Hz	D T N: 2 2 2	D T N: 16 16 8	D T N: 16 16 8	D T N: 16 16 8	D T N: 2 2 2	A	A	A	A	C
2 Normal Operation Monitoring @ 5 Hz	D T N: 2 2 2	D T N: 16 16 8	D T N: 16 16 8	D T N: 16 16 8	D T N: 2 2 2		A	A	A	C
3 Normal Start-Up Engineering @ 40 Hz		2 events	2 events	2 events			C	C	C	C
4 Normal Shut-Down Engineering @ 40 Hz		2 events	2 events	2 events			C	C	C	C
5 Emergency Shut-Down Engineering @ 40 Hz		2 events	2 events	2 events			C	C	C	C
6 Normal Operation Performance @ 0.5 Hz	D T N: 4 4 4	D T N: 4 4 4	D T N: 4 4 4	D T N: 4 4 4	D T N: 2 2 2		B	B	B	C

NOTES:
Data quantities represent the number of files.
Engineering Files are 10 minutes in duration
Monitoring files are 100 minutes in duration.
Performance files are 360 minutes in duration.

D Day (9 am to 4 pm)
T Transition (4 pm to 2 am)
N Night (2 am to 9 am)

A Higher priority
B Lesser priority
C Optional

Baseline Turbine Testing - Phase 4 Test Matrix

Test Configuration	*Data Collection Goal*					*Relative Priority*				
	<4 m/s	4-8 m/s	8-12 m/s	12-16 m/s	>16 m/s	<4 m/s	4-8 m/s	8-12 m/s	12-16 m/s	>16 m/s
1 Normal Operation Engineering @ 40 Hz	D T N: 2 2 2	D T N: 16 16 8	D T N: 16 16 8	D T N: 16 16 8	D T N: 2 2 2	A	A	A	A	C
2 Normal Operation Monitoring @ 5 Hz	D T N: 2 2 2	D T N: 4 4 4	D T N: 4 4 4	D T N: 4 4 4	D T N: 2 2 2		B	B	B	C
3 Normal Start-Up Engineering @ 40 Hz		5 events	5 events	5 events			A	B	A	C
4 Normal Shut-Down Engineering @ 40 Hz		5 events	5 events	5 events			A	B	A	C
5 Emergency Shut-Down Engineering @ 40 Hz		5 events	5 events	5 events			A	B	A	C

NOTES:
NOTES:
Data quantities represent the number of files.
Engineering Files are 10 minutes in duration
Monitoring files are 100 minutes in duration.

D Day (9 am to 4 pm)
T Transition (4 pm to 2 am)
N Night (2 am to 9 am)

A Higher priority
B Lesser priority
C Optional

Table 2. Completed test matrix

BASELINE TURBINE TESTING- PHASE 3 TEST MATRIX

TEST CONFIGURATION	Data Collection Goal														
	< 4 m/s			4-8 m/s			8-12 m/s			12-16 m/s			>16 m/s		
1) Normal operation	D	T	N	D	T	N	D	T	N	D	T	N	D	T	N
Engineering @ 40 Hz	2	2	2	16	16	8	16	16	8	16	16	8	2	2	2
2) Normal operation	2	2	2	16	16	8	16	16	8	16	16	8	2	2	2
Monitoring @ 5 Hz															
3) Normal Start-up				2 events			2 events			2 events					
Engineering @ 40 Hz															
4) Normal Shut-Down				2 events			2 events			2 events					
Engineering @ 40 Hz															
5) Emergency shut-down				2 events			2 events			2 events					
Engineering @ 40 Hz															
6) Normal operation	4	4	4	4	4	4	4	4	4	4	4	4	2	2	2
Performance @ 0.5 Hz															

TEST CONFIGURATION	Relative Priority				
	<4 m/s	4-8 m/s	8-12 m/s	12-16 m/s	>16 m/s
1) Normal operation	A	A	A	A	C
Engineering @ 40 Hz					
2) Normal operation		A	A	A	C
Monitoring @ 5 Hz					
3) Normal Start-up		C	C	C	C
Engineering @ 40 Hz					
4) Normal Shut-Down		C	C	C	C
Engineering @ 40 Hz					
5) Emergency shut-down		C	C	C	C
Engineering @ 40 Hz					
6) Normal operation		B	B	B	C
Performance @ 0.5 Hz					

TEST CONFIGURATION	Completed														
	<4 m/s			4-8 m/s			8-12 m/s			12-16 m/s			>16 m/s		
1) Normal operation	D	T	N	D	T	N	D	T	N	D	T	N	D	T	N
Engineering @ 40 Hz	0	0	0	43	0	45	74	0	10	37	10	41	17	0	0
2) Normal operation	0	0	0	11	0	1	15	0	1	8	0	1	0	0	0
Monitoring @ 5 Hz															
3) Normal Start-up					0			0			0			0	
Engineering @ 40 Hz															
4) Normal Shut-Down					0			0			0			0	
Engineering @ 40 Hz															
5) Emergency shut-down					0			0			0			0	
Engineering @ 40 Hz															
6) Normal operation	7	2	0	7	6	0	>4	>4	>4	>4	>4	>4	>2	>2	>2
Performance @ 0.5 Hz															

Notes:

Data quantities represent the number of files.	D- Day (9am to 4pm)	A- High priority
Engineering files (40 Hz) are ten minutes in duratio	T- Transition (4pm to 2am)	B- Lesser priority
Monitoring files (5 Hz) are 100 minutes in duration.	N- Night (2am to 9am)	C- Optional

3.2 Test Procedures

Tests on the CWE-300 were initiated by starting the central computer and the turbine. Once it was confirmed that both were operating properly, a table in the P2 Test Log Book was filled out with real-time sensor outputs (scaled to engineering units by the ADAS software). These values were compared to known correct values to check for malfunctioning sensors.

The test runs were started using the ADAS software. Each test had a specified maximum time, which was dictated by the sample rate and the 4 MB DAM memory limitation. At a sample rate of 40 hertz (Hz), the maximum test time was 100 minutes. At the end of the test, the central computer instructed the DAMs to download the data in memory to the central computer. The format of this data was a packed binary format proprietary to Zond. Converting the data to a usable ASCII format required the use of Zond's conversion software.

3.3 Test Data

The data collected during the testing of the P2 turbine consisted of operational data, including power output, wind speed, wind direction, temperature, and other variables. A total of 356.5 hours of data was collected at sample rates of 0.5 Hz, 5 Hz, and 40 Hz. A portion of the data was collected with the turbine shutdown for site calibration.

4.0 DATA PROCESSING

After downloading data from the DAMs to the central computer, the data was converted to a delimited ASCII format. Although scaling factors could have been applied during this conversion, the data was left unscaled. Because it was unscaled, the data files were pure voltage files.

After converting the data to the delimited ASCII format, the data was scaled from voltage files to engineering units. Some of the data channels also had to be calculated (e.g., yaw error, which used the data from the yaw position sensor and the wind direction sensor). Because each DAM created its own file, they were all combined into a single file as a part of the scaling process to make analysis of the data more efficient. The scaling, calculation, and combining of the files was accomplished with the IGOR Pro software.

Near the end of the project, ADAS II software was used instead of Zond's ADAS program. The ADAS II software was developed by Louis Manfredi under NREL sponsorship. ADAS II runs under Windows 95, whereas the Zond ADAS software runs under DOS program only. The ADAS II software has many advantages over ADAS, including the following:

(1) Long file name support (more descriptive names for data files).

(2) Automatic conversion of data to scaled engineering units in the data files. With ADAS only real time scaling was provided.

(3) Automatic combining of data from multiple DAMs into a single file.

(4) Simultaneous downloading of data from DAMs. With ADAS, the downloading was sequential.

(5) A graphical user interface.

(6) Multitasking (allowed analysis of data with IGOR Pro within five minutes of downloading data and while another test run was in progress).

5.0 OPERATIONAL TEST SENSORS

The operational sensors were used to measure external conditions, such as wind speed, wind direction, and various aspects of the operation of the turbine (e.g., power output).

Yaw Position (**YAWPOS**): This sensor was mounted on the tower top just below the main slip ring assembly. This measured the angle that the turbine nacelle made relative to the west guy cable direction. This was used as the zero reference point. It was difficult to keep it calibrated, as it was an incremental encoder, requiring the nacelle to be rotated 360 degrees to reset it. Because the yaw drive motor was unable to yaw the turbine in winds greater than 10 to 15 miles per hour, the sensor generally could not be reset. Even though it could not be reset, it still worked well, and allowed measurement of the yaw angle rate of change.

Tilt Position (**TLTPOS**): This sensor was mounted on the mainframe trunnion and the trunnion support. The tilt of the nacelle was measured over time with this sensor and from this, the tilt rate of the nacelle was determined.

Rotor Azimuth (**ROTRAZ**): This sensor consisted of a pair of proximity sensors mounted on the low-speed and high-speed shafts.

The angle of the blade from vertical was measured with these sensors. The sensors were calibrated so that when the black-tipped blade was pointed straight up, the angle was zero.

Nacelle Wind Speed (**NACWNS**): This anemometer was mounted on the upwind of the nacelle to measure the wind speed.

Yaw Error (**YAWERR**): This was measured using a wind vane mounted next to the nacelle wind speed sensor to measure wind direction. Using the YAWPOS data, the wind direction relative to the orientation of the nacelle could be calculated.

Nacelle Fore/Aft and Side-to-Side Acceleration (**NACFAA, NACSSA**): Two accelerometers mounted perpendicular to each other on a trunnion support measured the acceleration of the nacelle.

Low Speed Shaft (**LSSRPM**): This sensor measured the revolutions per minute (rpm) of the high-speed shaft. From this data, the rpm of the low-speed shaft could be calculated, as the gear ratio of the gearbox was known. Generally, the sensor was actually used to show the high-speed shaft rpm, as changes in that rpm were much more noticeable than those in the low-speed shaft.

Horizontal and Vertical Wind Speed and Direction- Hub Height and Lower Tip Height (**HUBWND, HUBWNS, LOWWNS, HUBVWS, LOWVWS**): These sensors were all mounted on the MET tower located northwest and slightly downhill from the turbine tower. The sensors consisted of wind vanes (wind direction, HUBWND), propeller anemometers (vertical wind speed, HUBVWS, LOWVWS), and cup anemometers (horizontal wind speed, HUBWNS, LOWWNS).

The hub height sensors (**HUBWND, HUBWNS, HUBVWS**) were located at the same relative height above the base of the MET tower as the turbine hub was located above the turbine tower base. The lower tip height (LOWWNS, LOWVWS) sensors were mounted at the same relative distance above the base of the MET tower as the lowest height that a blade tip reaches above turbine tower base. The relative heights were used with respect to the ground level, which consisted of a steep drop off in the prevailing wind direction.

Hub Height and Ground-Level Temperature (**HUBTMP, GNDTMP**): These sensors were mounted on the MET tower. The HUBTMP sensor was mounted at hub height (as defined above), and the GNDTMP sensor was mounted several feet above ground level at the base of the MET tower.

Barometric Air Pressure (**AIRPRS**): The barometric air pressure is measured at the base of the MET tower.

Power Output, Current, and Voltage (**PWROUT, CURENT, VOLTAG**): These sensors consisted of transducers connected to the generator output.

Status (**STATUS**): This is not a sensor per se; rather, it is a display of the binary states of various subsystems, showing whether the subsystem is on or off. These subsystems are described as follows:

(1) Parking brake

(2) Emergency stop

(3) Air flow sensor

(4) YAWERR vane

(5) Left-yaw detection

(6) Right-yaw detection

(7) Pitch-pump high-speed valve contactor

(8) Pitch-pump high-speed valve

(9) Pitch-pump low-speed valve

(10) Pitch pump

(11) Thyristor bypass contactor

(12) Generator contactor.

Digitally, the states of these subsystems are communicated as a 12-bit word, with each bit representing the state of the subsystem (i.e., on or off).

6.0 STRAIN GAGES

This section covers the location of the strain gages, how the gages were wired, the methods used to calibrate the gages, and whether the loads used to calibrate the gages were adequate. The term "calibration", as used herein, refers only to loading the components that the strain gages are attached to and measuring the voltage output, as no processing of the resulting data was carried out.

Not all of the strain gages originally envisioned were installed, and not all of the installed strain gages were calibrated. The reason calibration was not completed (including data processing), is that significant safety issues arose during the course of calibration that led to the decision to terminate all further testing. Therefore, many gages were left uncalibrated, and the data that had been acquired was only graphed and archived.

6.1 Strain Gage Calibration Procedures

The procedure to calibrate the gages involved applying known loads individually to the various components that had gages affixed to them, and then measuring the change in the gages' voltage output. Using data acquisition hardware and software, the voltage was measured and processed into a digital format for storage on a personal computer.

With the data collected from the calibration runs, the voltage outputs of the gages were compared with the loads applied. From this, the ratio of volts to pounds-force (lbf) and the zero offset was determined.

Using the slope and offset, the voltage signals from the strain gages were converted to engineering units and were stored in computer files in either a binary or a delimited ASCII format (depending on the signal processing-software used).

The equipment used to calibrate the strain gages included new load cells, ADAS boxes (Zond), DOS ADAS or ADAS II data acquisition and signal-processing software, and IGOR Pro for data analysis and graphing.

In Figure 7, the various pull points for calibration are described. Pull points:

- 1 and 4 were to be used for blade flat bending
- 2 and 3 were used for flexbeam flat bending
- 2 and 8 were used for flexbeam torsion
- 5 was to be used for blade-edge bending
- 6 was used for flexbeam-edge bending and low-speed shaft torsion
- 7 and 9 were used for low-speed shaft zero-degree bending
- 10 and 11 were pads for the nacelle to rest on which had anchor bolts to anchor the nacelle, if necessary
- 12 was used to hold the nose of the nacelle in place during other pulls.

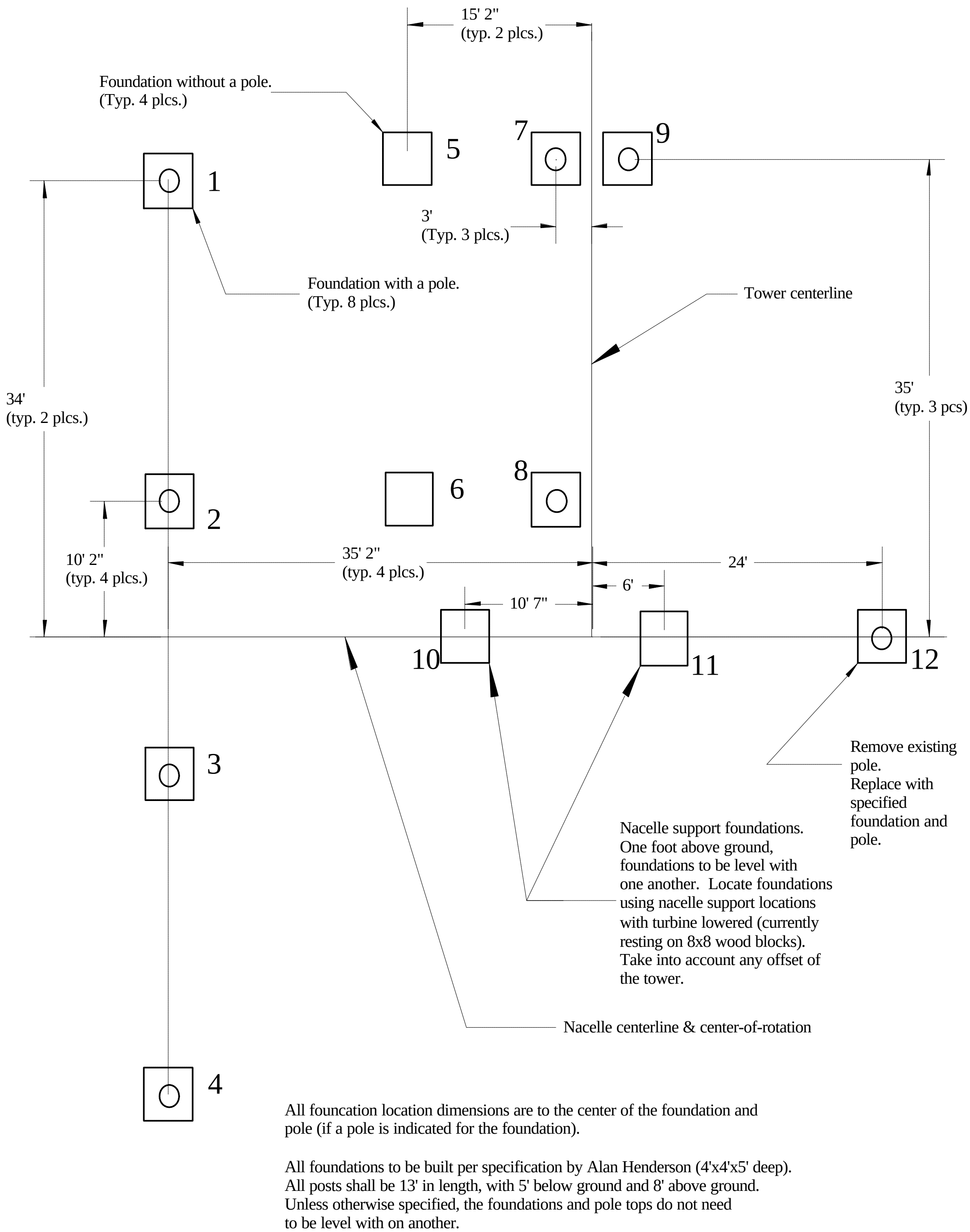

Figure 7. Layout of the pull points used for calibration

Figure 8. Installed pull points and the cement foundations for the anchors

The turbine itself had been removed before the picture was taken. However, the white bottom cover of the turbine is still on the tower.

6.2 Load Cell Calibration

For the calibration of the strain gages on the P2 turbine, factory-calibrated load cells were used to measure the loads applied to the various components. These load cells were calibrated by using one unused, factory-calibrated load cell with a hand held readout (both the load cell and its readout were dedicated to this use), and stringing the load cells to be calibrated in series with it between two rigid pull points. One end of this chain was attached to one of the pull points. The other was attached, via a cable, to a hand winch attached to another pull point.

A technician operated the winch to apply a tensile load to the chain of load cells. Another technician watched the handheld readout, and directed the winchtechnician. The load applied to the load cells was increased from zero to 2000 lbf in 200–500 lbf increments. When the load reached the desired value, the winchtechnician stopped turning the winch, and the operator at the data recording computer was advised that the desired load had been reached. The computeroperator then started a 20-second recording interval, noting the load at the beginning and end of the interval. The technicians then proceeded to the next load level.

After obtaining data for the load cell calibration runs, the data was imported to an Excel spreadsheet. For each of the 20-second intervals, the average load and voltage were calculated. Then, using a regression routine built into Excel, the slope and offset for each gage was determined.

After calculating the slope and offset, further calculations were made to arrive at the applied load using the average voltage output from the gages. This was compared with the average measured load. The percent difference between the measured and calculated loads was then calculated.

In general, the procedure outlined for calibrating load cells worked very well. For loads over 100 lbs, the percent difference between the measured and calculated loads was less than 0.50% and in most cases, was less than 0.20%.

The following graphs and tables detail the data that was acquired and how it was processed.

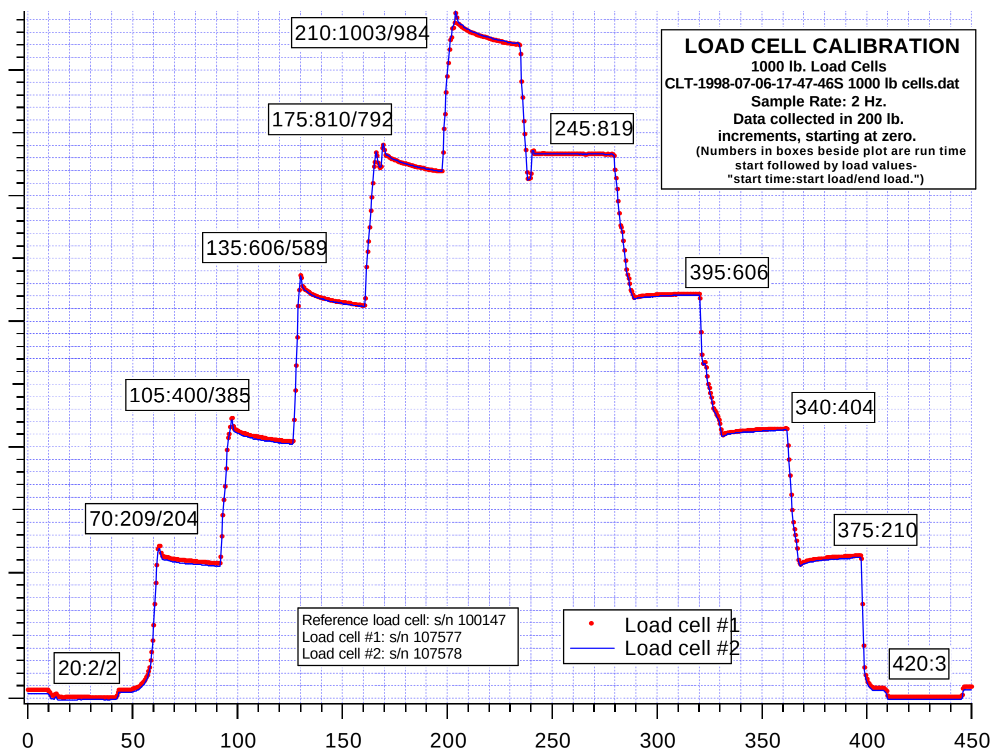

Figure 9. Calibration record for 1000 lbf load cells

Table 3. 1000 lbf regression analysis

1000 lbf Load Cells REGRESSION ANALYSIS										
Time Slice	Avg. Volts		Load			Calculated Loads				
	Cell 1	Cell 2	Start	End	Avg.	Cell 1	Cell 2	Error 1 %	Error 2 %
20-40	0.0000156	-0.0000276	2	2	2	1.0786423	2.5214318	-46.07	133.76
70-90	0.0021771	0.0021301	209	204	206.5	205.49997	205.19937	-0.48	-0.15
105-125	0.0041310	0.0040912	400	385	392.5	309.2995	389.41023	-0.56	-0.23
135-155	0.0063384	0.0063207	606	589	597.5	599.06623	598.83179	0.26	-0.04
175-195	0.0084654	0.0084689	810	792	801	800.23013	800.62301	-0.10	0.05
210-230	0.0105055	0.0105231	1003	984	993.5	993.17551	993.58201	-0.03	0.04
245-265	0.0086651	0.0086639	819	819	819	819.11785	818.94178	0.01	-0.02
295-315	0.0064235	0.0064017	606	606	606	607.12004	606.44449	0.18	-0.11
340-360	0.0042737	0.0042490	404	404	404	403.79679	404.23927	-0.05	0.11
375-395	0.0022423	0.0022104	210	210	210	211.66962	212.74104	0.80	0.51
420-440	0.0000247	-0.0000236	3	3	3	1.9409862	2.8937387	-35.30	49.09

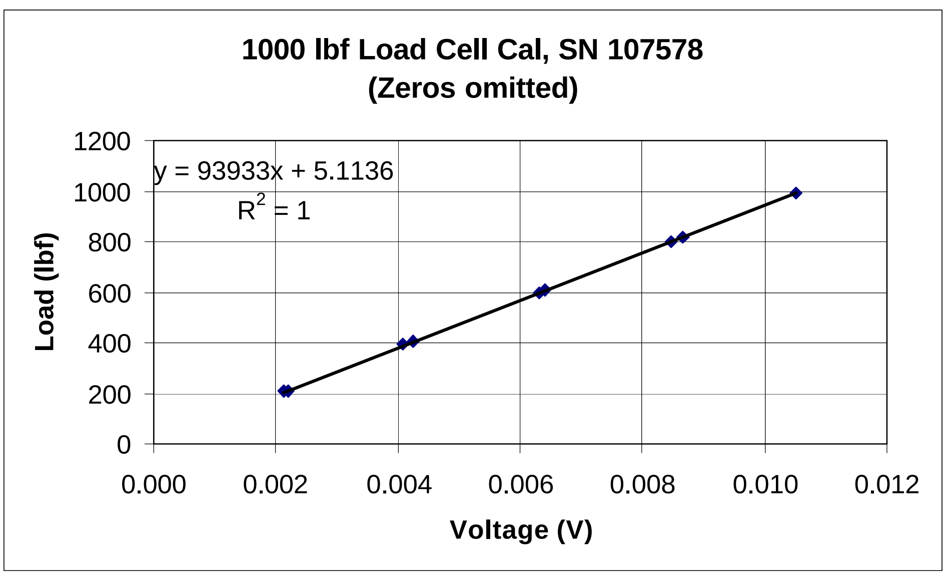

Figure 10. Regression function 1 for 1000 lbf

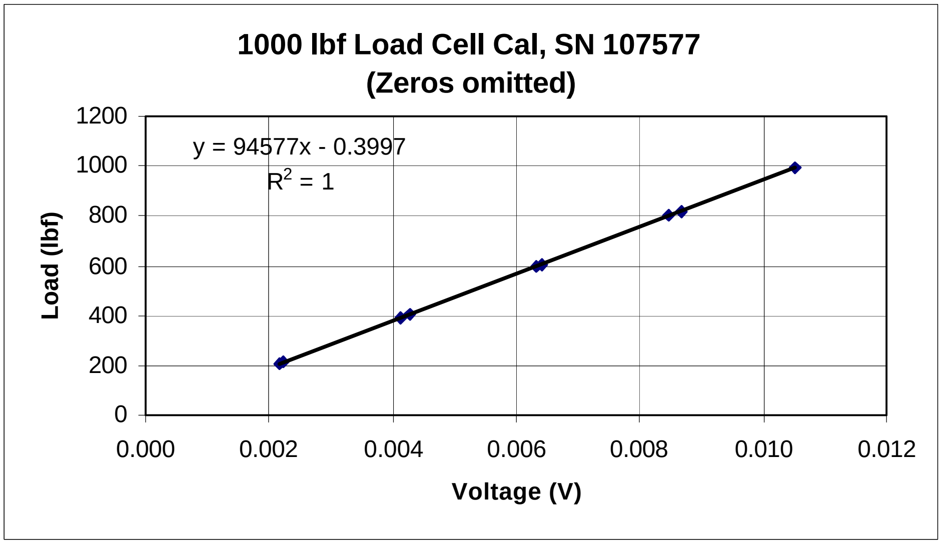

Figure 11. Regression function 2 for 1000 lbf

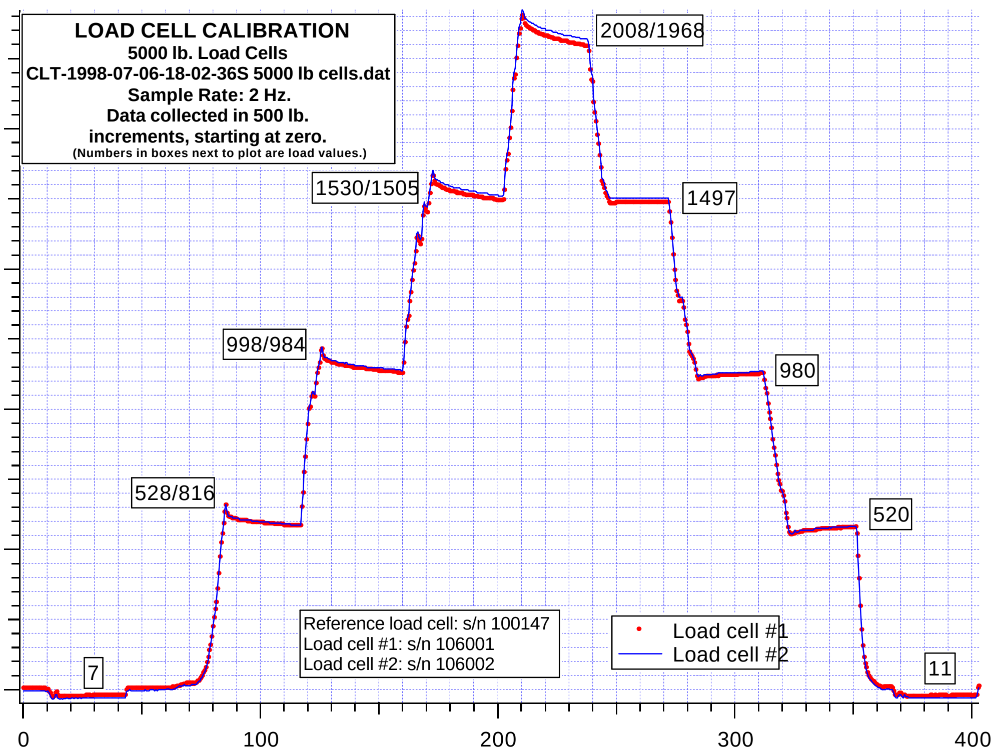

Figure 12. Calibration record for 5000 lbf load cells

Table 4. 5000 lbf regression analysis

5000 lbf Load Cells REGRESSION ANALYSIS									
Time Slice	Avg. Volts		Load			Calculated Loads			
	Cell 1	Cell 2	Start	End	Avg.	Cell 1	Cell 2	Error 1 %	Error 2 %
20-40	-3.98E-05	-5.97E-05	7	7	7	12.69	9.24	81.26	31.96
96-116	1.19E-03	1.19E-03	528	516	522	528.90	529.35	1.32	1.41
138-158	2.28E-03	2.30E-03	998	984	991	991.70	991.43	0.07	0.04
175-195	3.54E-03	3.57E-03	1530	1505	1517.5	1522.26	1522.80	0.31	0.35
215-235	4.64E-03	4.69E-03	2008	1968	1988	1986.31	1987.02	-0.08	-0.05
250-270	3.48E-03	3.51E-03	1497	1497	1497	1496.02	1494.64	-0.07	-0.16
290-310	2.25E-03	2.26E-03	980	980	980	976.13	975.84	-0.39	-0.42
330-350	1.15E-03	1.15E-03	520	520	520	514.18	514.41	-1.12	-1.08
380-400	-4.02E-05	-5.91E-05	11	11	11	12.51	9.48	13.71	-13.84

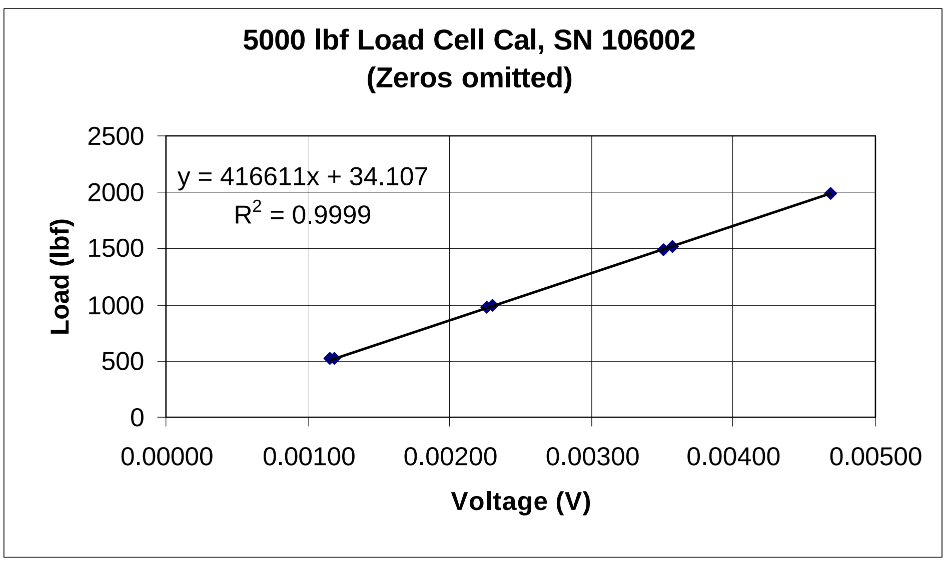

Figure 13. Regression function 1 for 5000 lbf

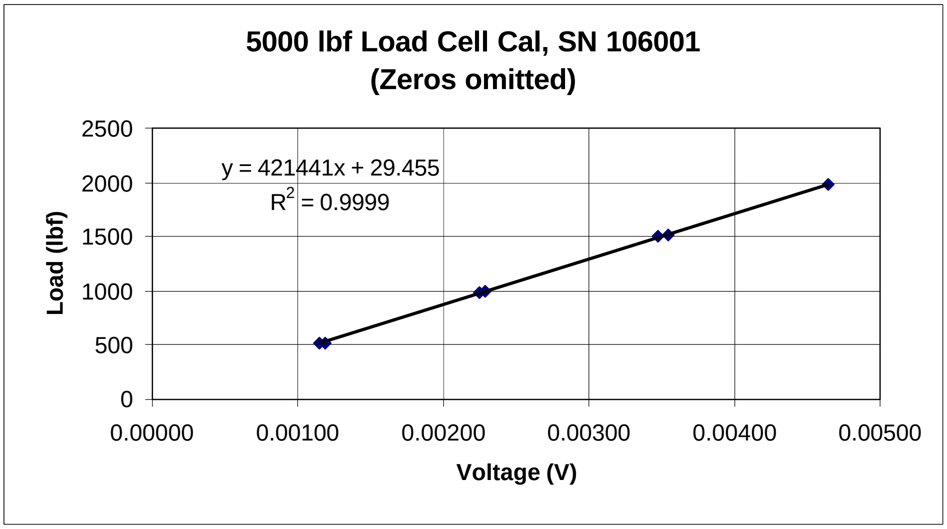

Figure 14. Regression function 2 for 5000 lbf

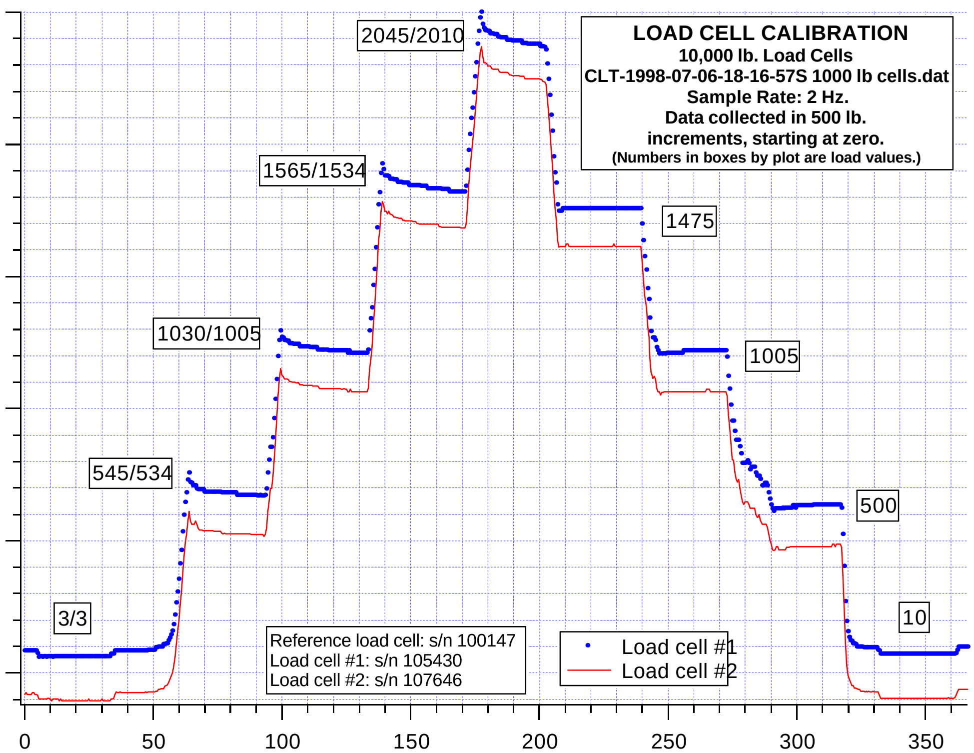

Figure 15. Calibration record for 10000 lbf load cells

Table 5. 10000 lbf regression analysis

10,000 lbf Load Cells REGRESSION ANALYSIS								
Avg. Volts		Load			Calculated Loads			
Cell 1	Cell 2	Start	End	Avg.	Cell 1	Cell 2	Error 1 %	Error 2 %
0.000064	-0.000106	3	3	3	5.4629713	-1.2365755	82.10	-122.64
0.000681	0.000530	545	534	539.5	540.49397	543.66864	0.18	0.59
0.001229	0.001082	1030	1005	1017.5	1015.4946	1017.2783	-0.20	0.18
0.001842	0.001701	1565	1534	1549.5	1547.1931	1547.6892	-0.15	0.03
0.002397	0.002265	2045	2010	2027.5	2028.8796	2030.7886	0.07	0.09
0.001759	0.001614	1475	1475	1475	1475.5212	1473.3217	0.04	-0.15
0.001218	0.001065	1005	1005	1005	1006.5558	1002.6967	0.15	-0.38
0.000634	0.000478	500	500	500	499.85755	499.18464	-0.03	-0.13
0.000074	-0.000096	10	10	10	13.805964	7.2956519	38.06	-47.16

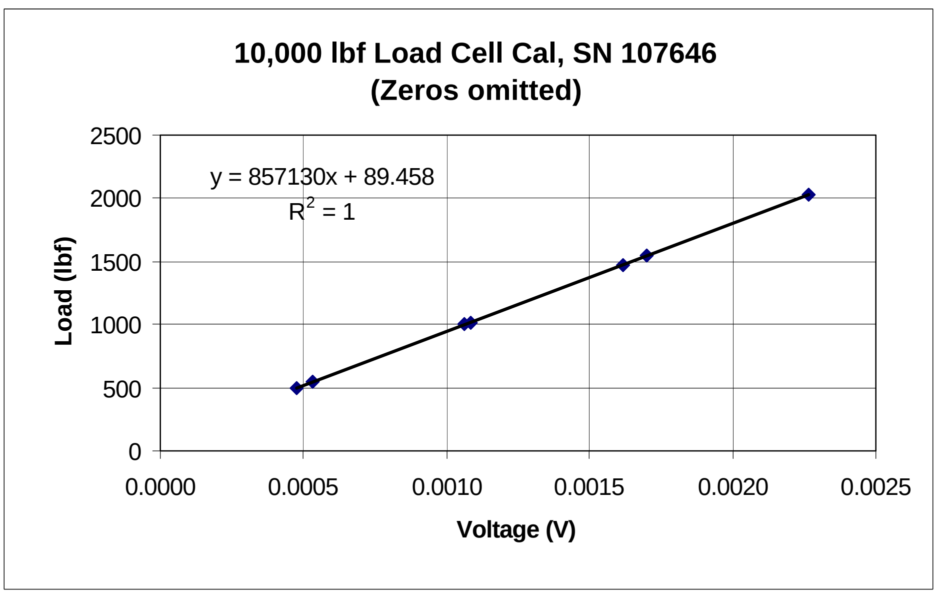

Figure 16. Regression function 1 for 10000 lbf

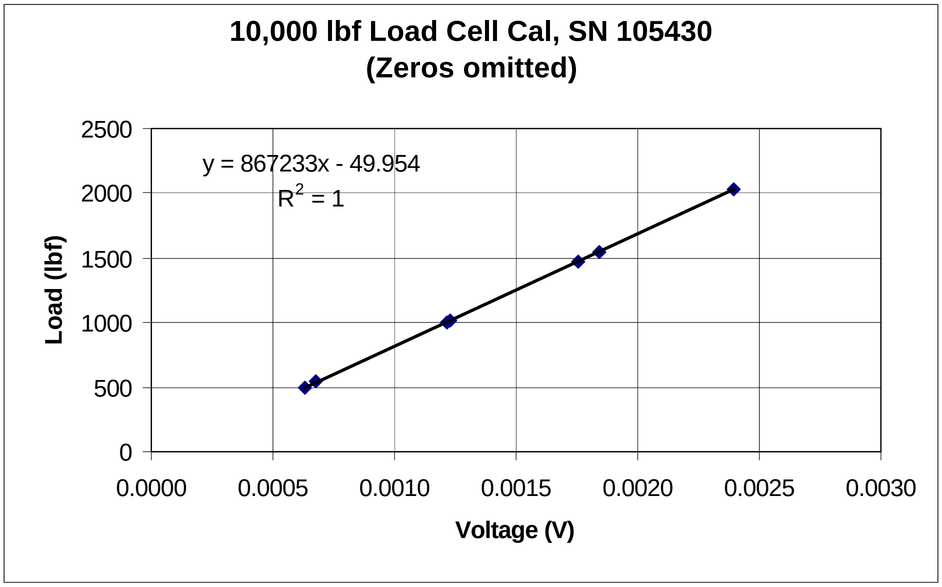

Figure 17. Regression function 2 for 10000 lbf

6.3 Strain Gage Calibration

Once the load cells were calibrated for use with the ADAS hardware, calibration of the strain gages began. The strain gages that were calibrated were located on the flexbeam and the low-speed shaft. The calibration data was only collected and graphed; the performance testing part of the project was terminated before any of the data was processed.

On the flexbeam, three pairs of strain gages were calibrated. Each was a full bridge configuration. These included edge-bending, flat-bending, and torsion of the flexbeam.

On the low-speed shaft, two pairs of strain gages were calibrated. Each of these was in a full bridge configuration. These gages were used to measure low-speed shaft torsion and zero-degree bending (i.e., along the blade axis).

Flexbeam Edge-Bending and Low Speed Shaft Torsion The flexbeam edge-bending strain gages and the low-speed shaft torsion gages were calibrated at the same time, as the method of loading each was the same. In order to calibrate the flexbeam edge-bending gages and the low-speed shaft torsion gages, the flexbeam was leveled (i.e., made horizontal) and the one-way clutch was locked into place to prevent rotation of the low-speed shaft. Then a vertical load was applied to one end of the flexbeam, in the direction of blade rotation.

In order to achieve a vertical load, a pulley was attached to a bolt anchored in a cement foundation. The cable used to load the flexbeam was run through the pulley, connecting the load cell to the winch on a pull point. Another cable was attached to the pulley case and attached to a winch on another pull point. Using this second cable, we were able to move the pulley so that the cable going up to the load cell was vertical. The reason for the aforementioned alignment procedure is that the nacelle comes down in different positions depending on the wind direction at the time of lowering as the tower bends in the wind. Therefore, some fine-tuning of the pulley position was required.

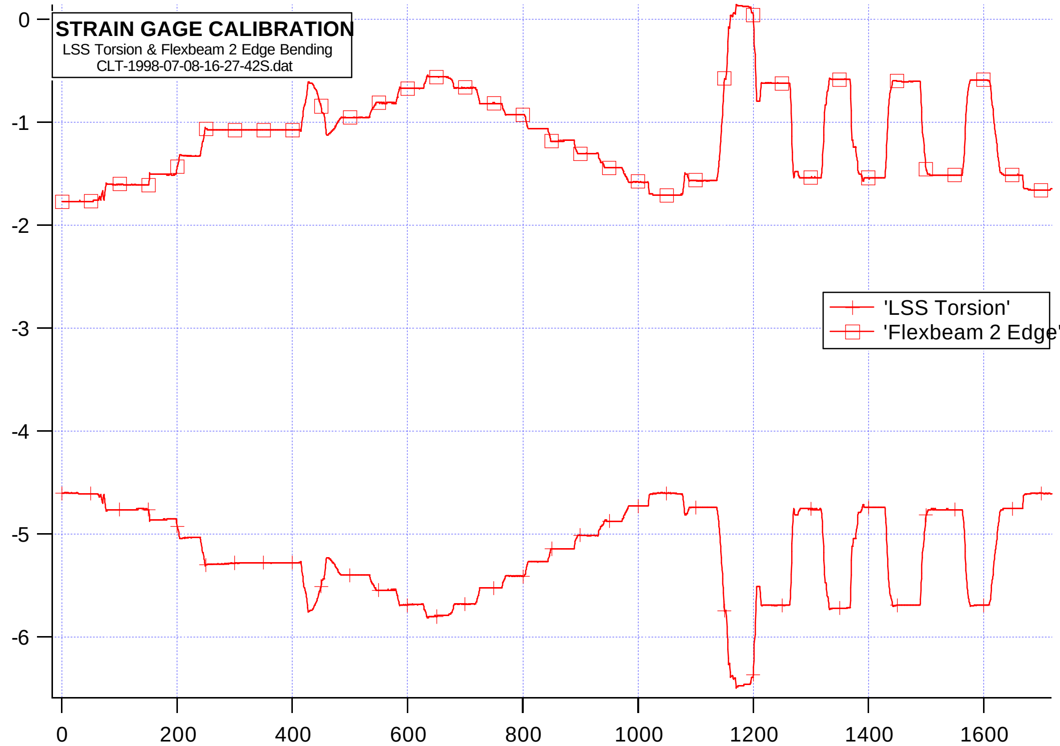

Figure 18. Calibration graph for flexbeam and low speed shaft

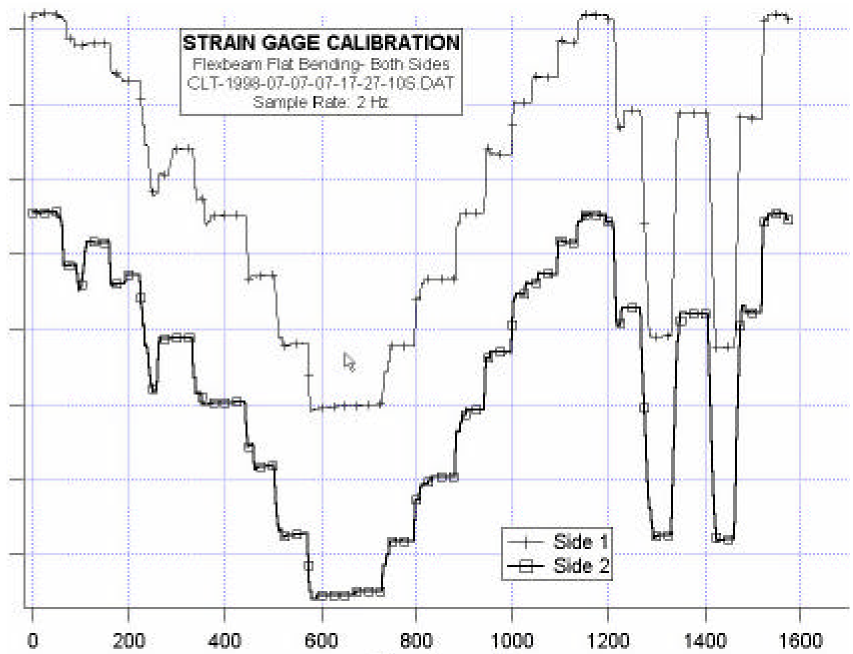

Figure 19. Calibration graph for the flat bending strain gages

Flexbeam Flat-Bending Flexbeam flat-bending was measured by attaching load cells and cables to each end of the flexbeam and applying loads to them using the winches. The cables were pulled perpendicular to the flexbeam in its unloaded state. The nose of the nacelle was anchored to prevent the turbine from sliding or rising off the ground.

The same loading procedure as that outlined above for calibrating the load cells was used to apply loads to the flexbeam.

Flexbeam Torsion Flexbeam torsion was calibrated by attaching a steel angle iron to the ball joint at an end of the flexbeam. At a distance of 2 feet above and below the center of the ball joint, load cells and cables were attached. Winches were used to pull the angle iron. The cables were perpendicular to the angle iron before a load was applied.

The same procedure as outlined for calibrating the load cells was used.

The data that we obtained is of limited use, other than to show that the strain caused by torsion at the location of the strain gage is very small. The signal that we obtained from the gage was so small that operation of a hand held radio within 20 feet of the gages caused significant interference. Further, the voltages obtained from the gages ranged from 450 microvolts (V) to 560 V, a difference of only 110 V.

The following graph and image shows the data acquired and the load method during this calibration.

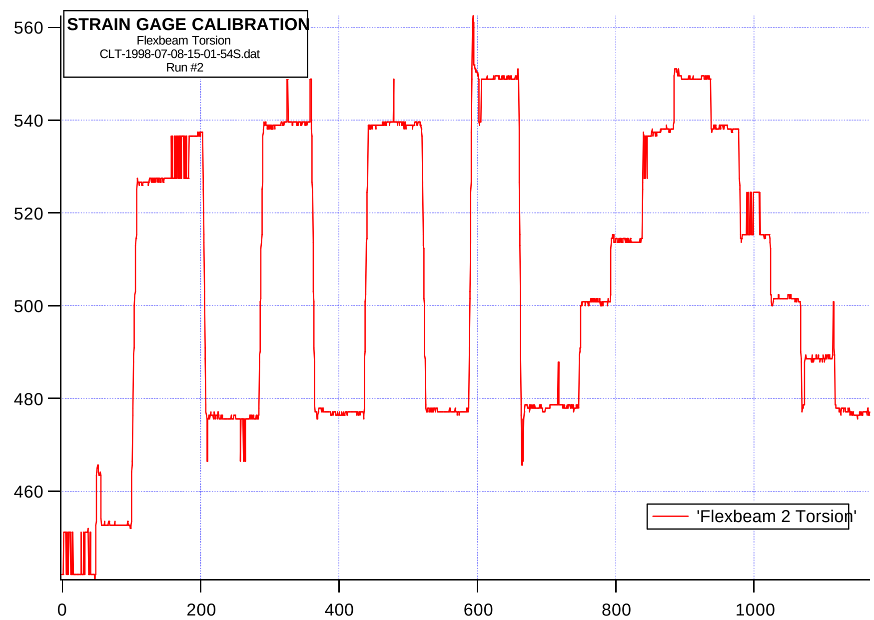

Figure 20. Output from the flexbeam torsion strain gages

Low-Speed Shaft Zero-Degree Bending The low-speed shaft (LSS) zero-degree bending was accomplished by attaching a load cell and cable to the upwind end of the generator and to the hub. Using winches, the whole nacelle was subjected to a bending moment about the mainframe pivot point.

The same loading procedure as that outlined above for calibrating the load cells was used to apply loads to the low-speed shaft.

Figure 21. Calibration setup for low-speed shaft zero-degree bending 1

Figure 22. Calibration setup for low-speed shaft zero-degree bending 2

Figure 23. Calibration setup for low-speed shaft zero-degree bending 3

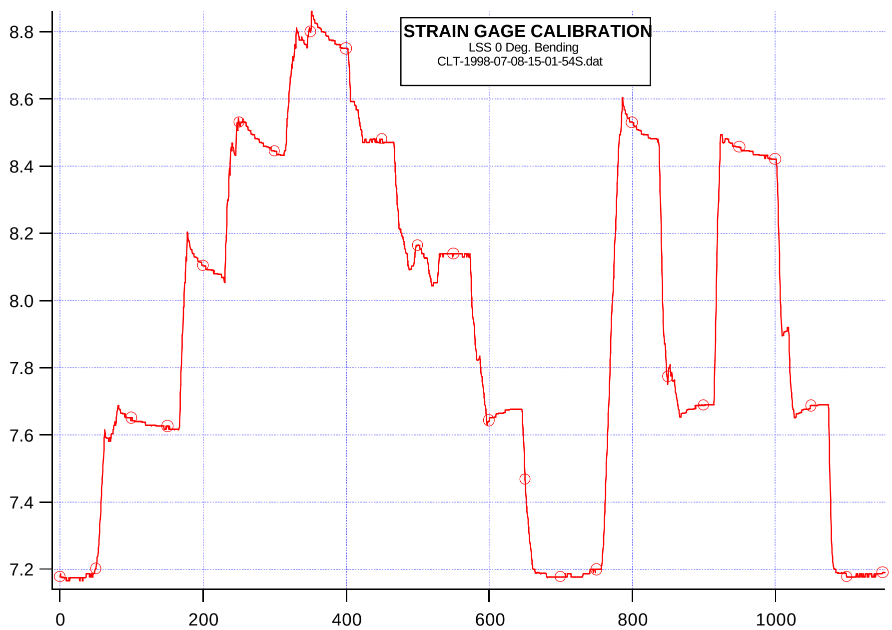

Figure 24. Calibration graph for low-speed shaft zero-degree bending

6.4 Comments Concerning Calibration Procedures

Using the data acquisition system with the ADAS II software to record and process load data from the load cells contemporaneously with the recording and processing of the strain gage data worked extremely well. This method gave more reliable and accurate load data than using the load cell hand held readouts separately from the data acquisition system.

The tested strain gages gave excellent signals that were more than adequate for calculating the slopes and offsets of the gages. The loads applied during the calibration were adequate for calibrating the gages, so long as we are correct in assuming that the gage output is linear throughout the operating load range. The only exception to this was the flexbeam torsion gage, which was not sensitive enough.

The use of the ADAS II software and its graphical user interface gave an excellent view of the data in real time, which allowed for immediate confirmation of the data integrity. The ADAS II software downloaded data from multiple data acquisition modules simultaneously, and it automatically converted the data to engineering units in delimited ASCII format. This allowed us to use IGOR Pro to process the data into a graphical format within about five minutes of the download. We were able to check for anomalous signals or unusual conditions in a timely and efficient manner. However, because of the premature termination of the testing, this software was never used to record and process operational test data.

7.0 LOADS AND STRESSES

During instrument calibration, the proof loads applied to the turbine components were considerably less than the maximum operating loads predicted by PROP, YAWDYN, and the ADAMS model. There was discussion about loading the components to their expected operating loads; however, it was decided to use lesser loads for reasons of safety and practicality. The loads actually used were based largely on the loads that NREL used to calibrate the P1 turbine in Colorado.

Other considerations included concerns about whether the tilt damper, with existing cracks, could withstand maximum operational loading. Because of these fatigue cracks and inadequate test supports, lower-proof load values were used for calibration. At the time of calibration, it was unclear as to what the maximum operating loads were, varying significantly among the computer models. The test equipment needed to apply maximum operational loads would have required significant tooling, set-up time, and support equipment, such as cranes or electric motors. Compared to equipment designed to withstand loads of as much as 2000 lbf, such equipment could not be designed, acquired, and put into place within the time frame of the project.

Although full loads were not applied to the components, the signals received from the strain gages were sufficient to calculate reliable and accurate slopes and offsets for performance data acquisition. Again, this is assuming that the gage output would remain linear up to the maximum operating load.

Table 6. Comparison of loads

Comparison of Predicted Pull Test Load vs. Actual Loading
Note: The predicted pull test loads were calculated and may represent only a percentage of the expected full operational loading.

Component	Predicted Pull Test Load (lbf)	Actual Load (lbf)	Percentage of Predicted Load
Low Speed Shaft Torque	5500	2000	36.4 %
Low Speed Shaft Zero Degree Bending	11100	5000	45.0 %
Flexbeam Edge Bending	2900	2000	69.0 %
Flexbeam Flat Bending	10900	1200	11.0 %
Flexbeam Torsion	3100	500	16.1 %

8.0 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE TESTING

The data acquisition system worked very well, despite problems with the DAM in the nacelle, which was extremely sensitive to power spikes in the power grid. Because the ADAS II software has many improvements over the original ADAS software, it is highly recommended for use with the ADAS hardware.

The test procedures were adequate for the testing performed as the procedures involved a data integrity check at the beginning of each test run, and the sensors generally functioned very well throughout the testing. However, additional surge protection should be considered.

The sensors used were all adequate for their intended use, and similar sensors are recommended for future testing.

Based on the calibration tests that were performed, the methods, procedures, hardware, and software described above could be used for acquiring reliable and accurate strain gage performance data from the operation of a CWE-300 type of turbine. The locations of the strain gages appear to be adequate for performance data acquisition. However, the flexbeam torsion gage may need to be moved further from the center of rotation to increase the signal from the gage.

It is highly recommended that load cells of some sort be used with the data acquisition system to record load data simultaneously with the data acquired from the strain gages. This method will significantly improve the efficiency and accuracy of the data acquisition.

9.0 POWER CURVES

The power curve for the CWE-300 was predicted using the software PROPID. Because of blade-pitch with coning of the CWE-300 design, the PROPID output had to be interpolated among sweeping angles of attack. This method should be used to represent the increasing blade-pitch toward stall as the coning angle increases in higher winds. However, the following analysis does not consider this for simplicity.

9.1 Predicted Power Curve

The power curve of a wind turbine describes the relationship between power output and average wind speed. It is required in order to estimate the energy that a turbine will produce at a particular site. The power output is affected by environmental factors such as altitude (air density) and wind shear. Also, turbine parameters such as the blade-pitch angle and tower height can be selected to maximize energy output and minimize overall cost of energy at a specific site. In order to achieve the best performance, information about the site for which the power curve is to be derived is necessary. This section presents the power curve as a function of air density for the CWE-300 turbine with a 96 feet diameter rotor on a 48.8 meters guyed tower. Note that the effect of turbulence on the power curve is not included. This was the configuration of the P2 preproduction prototype.

Description of Power Curves The power curves presented in this section were all derived using PROPID. This program predicts performance for both stall-regulated and pitch-regulated rotors. The CWE-300 turbine has a stall-regulated rotor, although it does employ full-span pitching towards stall to brake the rotor. The operating pitch angle is adjustable; however, it is likely to be adjusted simply for the average air density of a given site (typically computed from the altitude), or at most twice a year if the site experiences large seasonal temperature changes. The power curves presented here were computed over a range of air densities.

PROPID computes rotor power, which must then be adjusted to obtain electrical power output after inclusion of gearbox and generator losses. An efficiency curve for the two-stage, planetary gearbox, obtained from the report *Flexible Turbine Model Description* (Dynamic Design, 1997), is shown in Figure 25. A second-order polynomial was fit to the gearbox efficiency curve, thus providing a direct calculation of efficiency (and corresponding losses) as a function of power output. Table 7 shows values of the gearbox efficiency polynomial coefficients.

The efficiency curve for the generator is shown in Figure 26. This curve is based on the manufacturer's specifications of the CWE-300 generator and was not specifically measured. As with the gearbox efficiency curve, a polynomial function was fit to the generator efficiency curve to make loss computations easier. The coefficients values of the efficiency polynomial are provided in Table 7. The *'y'* in the polynomial functions stands for efficiency.

$y = a + bP + cP2$

$yGbox = 2.7 + 0.015P + 10\text{-}5\ P2$

$yGen = 3.5 + 0.04P + (2 \times 10\text{-}5)\ P2$

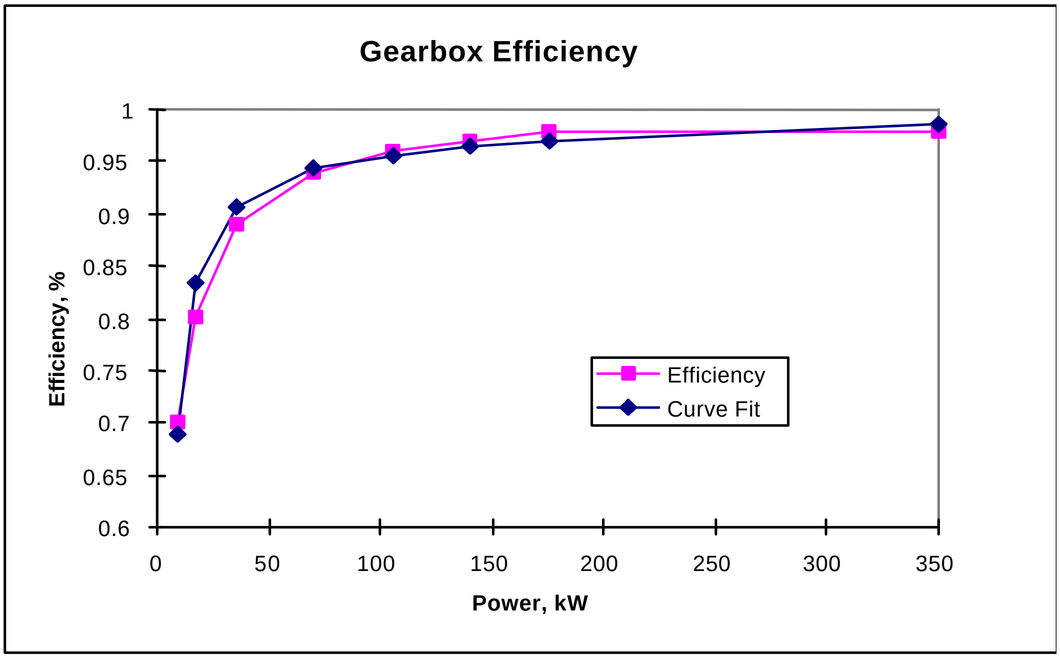

Figure 25. Gearbox efficiency curve and fit

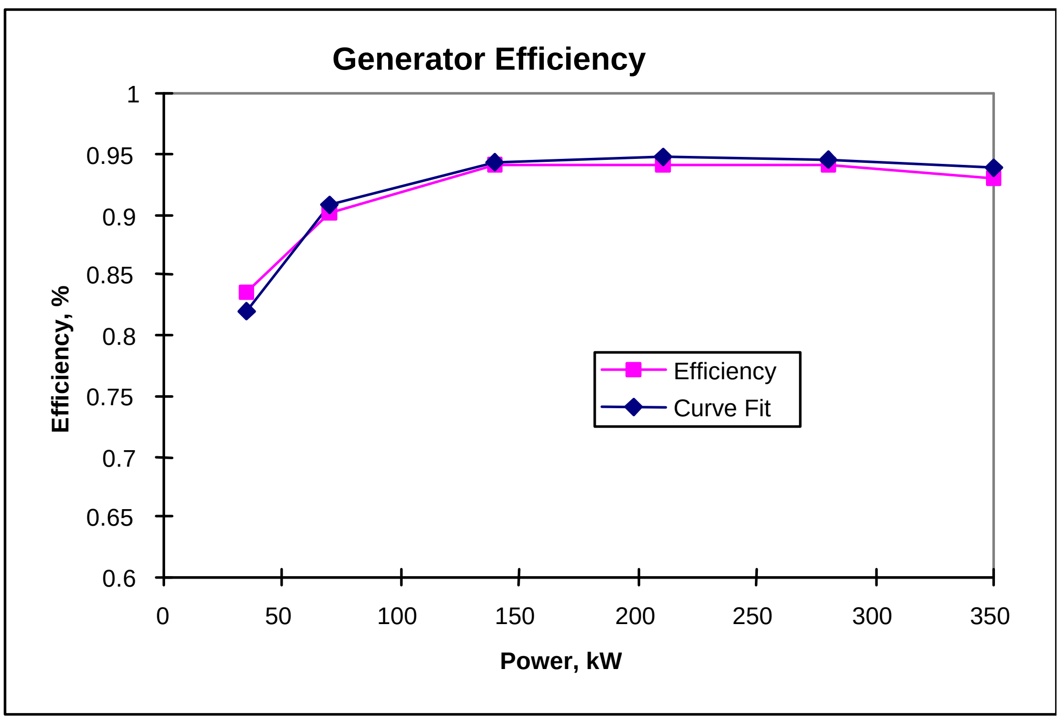

Figure 26. Generator efficiency curve and fit

Table 7. Curve-fit losscoefficients for gearbox and generator

	Gearbox	Generator
Constant	2.7	3.5
Linear Coef. (P)	0.015	0.04
Quadratic Coef. (P2)	0.00001	0.00002

The turbine configuration for these power curve calculations includes the 96 foot (29.3 meter) diameter rotor, mounted on a 160 foot (48.8 meter) tower. The standard wind shear power law of 0.14 was assumed for calculating the impact of shear on the power output. The rotor rotational speed of 55.95 rpm was used in the calculations. This represents the speed at full nominal power (300-kW).

Power Curves as Function of Air Density The power curve for the CWE-300 turbine was computed for a range of air densities. Air density is a function of altitude and temperature. Table 8 illustrates air density over a wide altitude and temperature range. PROPID was used to generate a family of power curves for a range of densities. The entire matrix was not run; however, power curves may be interpolated to obtain intermediate values. The operating pitch angle was adjusted for each value of density to achieve the proper peak-rated power.

Table 8. Air density

Altitude, m	Temperature, deg. C				
	0	10	15	25	35
0	1.292	1.247	1.225	1.184	1.145
500	1.217	1.174	1.154	1.115	1.079
1000	1.146	1.106	1.086	1.050	1.016
1500	1.078	1.040	1.022	0.988	0.956
2000	1.014	0.978	0.961	0.929	0.898

Table 9 shows the air density and operating pitch angle for each case that was run. It further shows that it is very important to know the site characteristics so that the run pitch angle may be properly adjusted. Running off the optimum will either cause the turbine to under- or overproduce and possibly damage the hardware.

Table 9. Summary of power curve cases

Case	Air Density, kg/m3	Run Pitch Angle, deg.
	1.225	0.5
	1.200	0.8
	1.150	1.3
	1.100	1.5
	1.050	2.3
	1.000	2.8

The following pages present the power curves for each case listed in Table 9 in both tabular and graphical form. Each page includes, in addition to electrical power as a function of wind speed, parameters defining the turbine configuration and the assumed operating conditions.

CWE-300 Wind Turbine Power Curve

Rotor Diameter (m)	29.3
Hub Height (m):	48.8
Rotor Speed (rpm)	55.33
Turbine rated power (kW)	300
Run pitch angle (deg)	0.5
Air density (kg/m^3)	1.225

Date Created	5/23/97
Created by	R. Marsh
Power Curve I.D.	970523RM01

Wind Speed (m/s)	Net Power (kW)
1	0
2	0
3	0
4	0
5	8.1
6	28.9
7	56.7
8	86.1
9	110.5
10	145.9
11	177.0
12	209.9
13	241.0
14	265.9
15	286.0
16	304.8
17	315.1
18	315.7
19	314.0
20	311.0
21	308.5
22	306.9
23	306.4
24	306.6
25	307.3
26	308.3
27	309.4
28	310.7
29	312.0
30	313.4
31	314.8

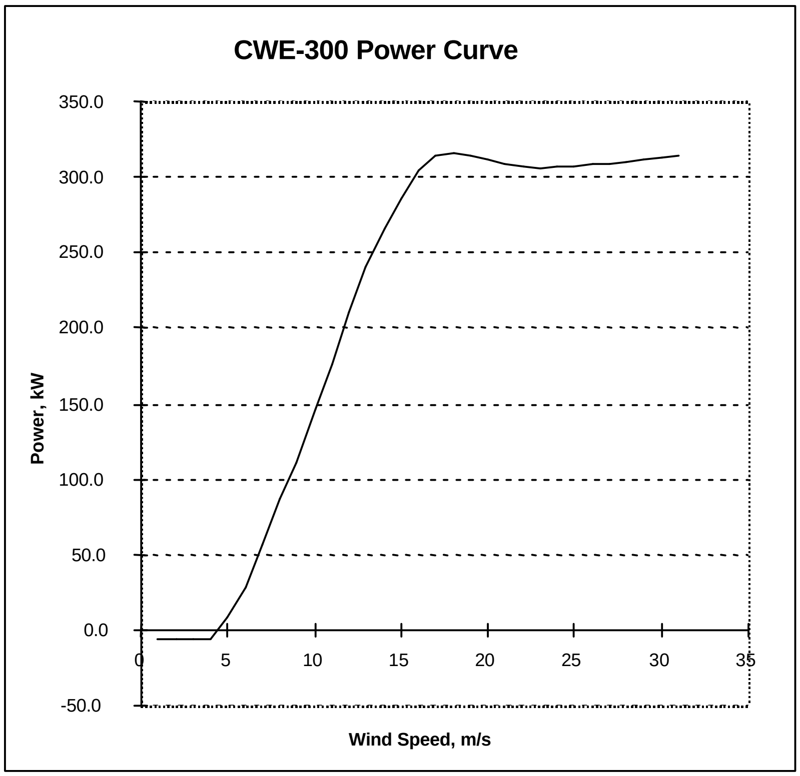

Figure 27. Power curve for run pitch angle 0.5-degree

CWE-300 Wind Turbine Power Curve

Rotor Diameter (m)	29.3
Hub Height (m):	48.8
Rotor Speed (rpm)	55.33
Turbine rated power (kW)	300
Run pitch angle (deg)	0.8
Air density (kg/m^3)	1.2

Date Created	5/23/97
Created by	R. Marsh
Power Curve I.D.	970523RM06

Wind Speed (m/s)	Net Power (kW)
1	0.0
2	0.0
3	0.0
4	0.0
5	8.6
6	28.7
7	55.6
8	85.3
9	109.4
10	140.5
11	172.4
12	203.0
13	234.3
14	260.6
15	282.0
16	300.6
17	313.3
18	317.6
19	316.7
20	314.1
21	311.1
22	309.3
23	308.5
24	308.5
25	309.1
26	310.1
27	311.2
28	312.6
29	314.0
30	315.5
31	317.0

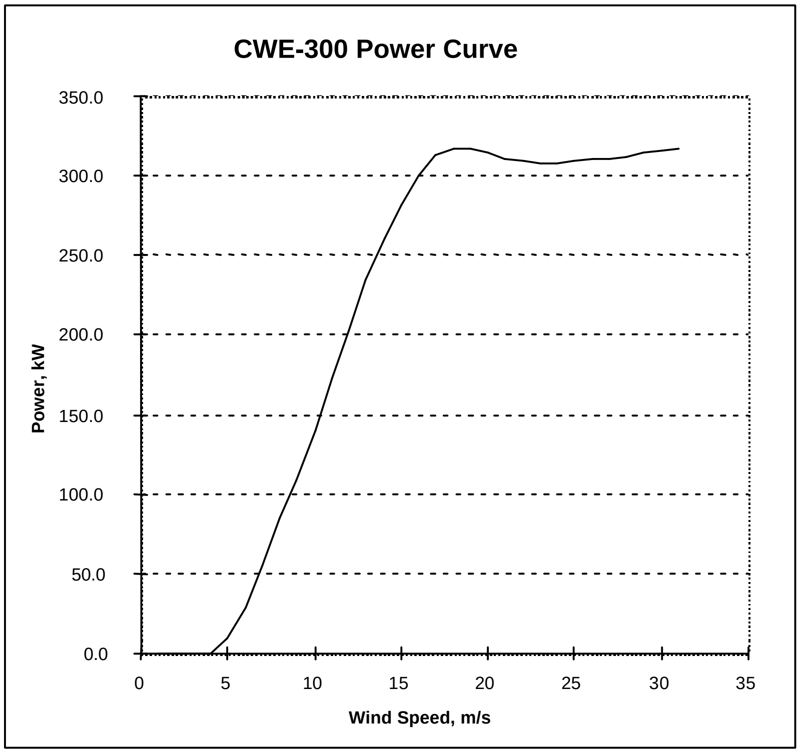

Figure 28. Power curve for run pitch angle 0.8-degree

CWE-300 Wind Turbine Power Curve

Rotor Diameter (m)	29.3
Hub Height (m):	48.8
Rotor Speed (rpm)	55.33
Turbine rated power (kW)	300
Run pitch angle (deg)	1.3
Air density (kg/m^3)	1.15

Date Created	5/23/97
Created by	R. Marsh
Power Curve I.D.	970523RM05

Wind Speed (m/s)	Net Power (kW)
1	0.0
2	0.0
3	0.0
4	1.8
5	14.5
6	32.7
7	57.1
8	85.3
9	110.7
10	135.9
11	168.0
12	197.5
13	228.5
14	259.1
15	284.8
16	305.8
17	322.0
18	332.7
19	335.7
20	333.6
21	330.3
22	327.6
23	326.1
24	325.6
25	326.0
26	327.1
27	328.5
28	330.0
29	331.8
30	333.6
31	335.6

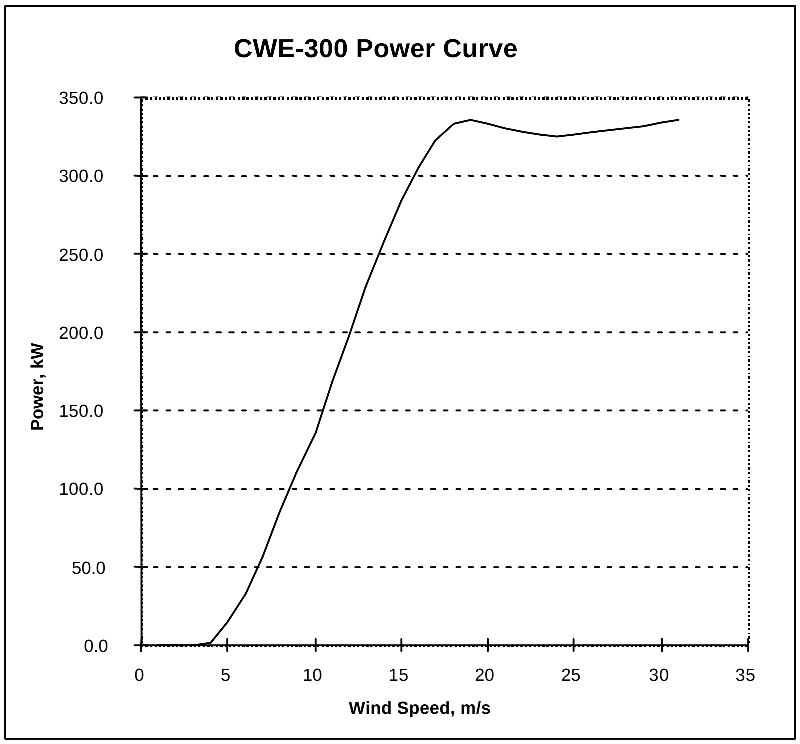

Figure 29. Power curve for run pitch angle 1.3-degree

CWE-300 Wind Turbine Power Curve

Rotor Diameter (m)	29.3
Hub Height (m):	48.8
Rotor Speed (rpm)	55.33
Turbine rated power (kW)	300
Run pitch angle (deg)	1.5
Air density (kg/m^3)	1.1

Date Created	5/23/97
Created by	R. Marsh
Power Curve I.D.	970523RM02

Wind Speed (m/s)	Net Power (kW)
1	0
2	0
3	0
4	0
5	8.7
6	26.6
7	50.3
8	77.4
9	103.1
10	125.3
11	155.0
12	182.1
13	209.2
14	237.8
15	261.6
16	280.5
17	294.7
18	305.8
19	310.2
20	308.8
21	306.1
22	303.5
23	302.1
24	301.4
25	301.7
26	302.6
27	303.8
28	305.1
29	306.7
30	308.4
31	310.1

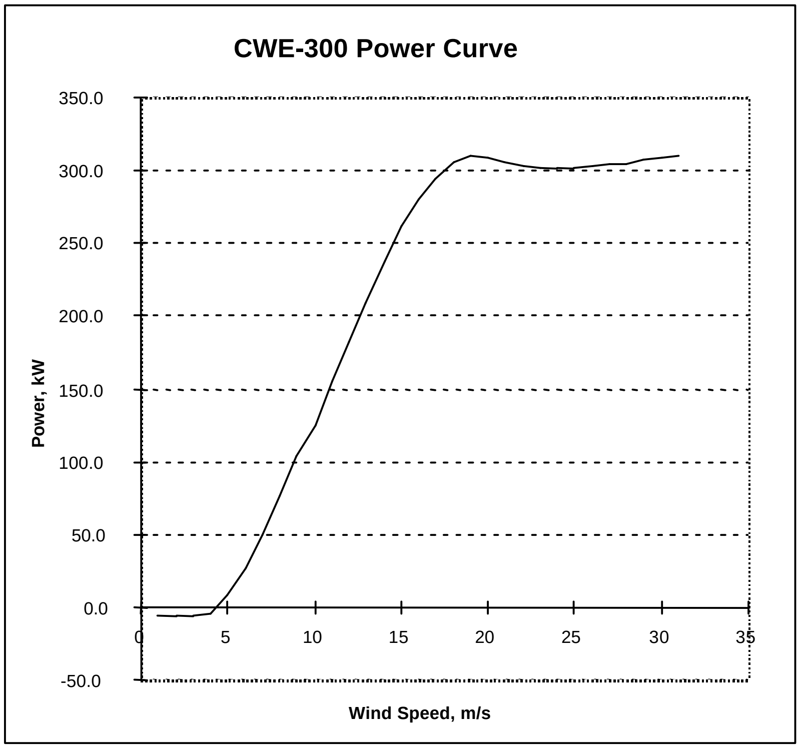

Figure 30. Power curve for run pitch angle 1.5-degree

CWE-300 Wind Turbine Power Curve

Rotor Diameter (m)	29.3
Hub Height (m):	48.8
Rotor Speed (rpm)	55.33
Turbine rated power (kW)	300
Run pitch angle (deg)	2.3
Air density (kg/m^3)	1.05

Date Created	5/23/97
Created by	R. Marsh
Power Curve I.D.	970523RM04

Wind Speed (m/s)	Net Power (kW)
1	0.0
2	0.0
3	0.0
4	0.0
5	8.6
6	25.3
7	46.1
8	70.3
9	96.9
10	120.8
11	143.1
12	169.6
13	195.5
14	221.3
15	247.8
16	270.2
17	288.1
18	303.1
19	313.6
20	316.5
21	314.9
22	312.1
23	309.7
24	308.4
25	308.0
26	308.4
27	309.4
28	310.9
29	312.4
30	314.3
31	316.2

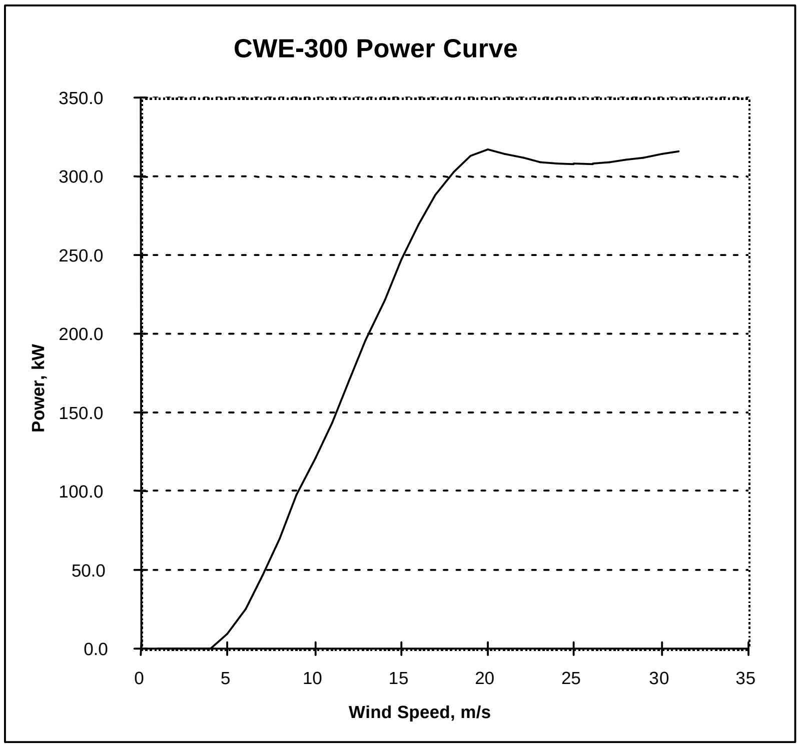

Figure 31. Power curve for run pitch angle 2.3-degree

CWE-300 Wind Turbine Power Curve

Rotor Diameter (m)	29.3
Hub Height (m):	48.8
Rotor Speed (rpm)	55.33
Turbine rated power (kW)	300
Run pitch angle (deg)	2.8
Air density (kg/m^3)	1.000

Date Created	5/23/97
Created by	R. Marsh
Power Curve I.D.	970523RM03

Wind Speed (m/s)	Net Power (kW)
1	0.0
2	0.0
3	0.0
4	0.0
5	7.4
6	22.8
7	41.6
8	63.9
9	88.9
10	113.9
11	135.1
12	158.3
13	183.4
14	207.1
15	232.0
16	256.5
17	276.3
18	291.8
19	303.8
20	311.6
21	313.3
22	311.0
23	308.4
24	306.6
25	305.7
26	305.7
27	306.4
28	307.8
29	309.3
30	311.2
31	313.2

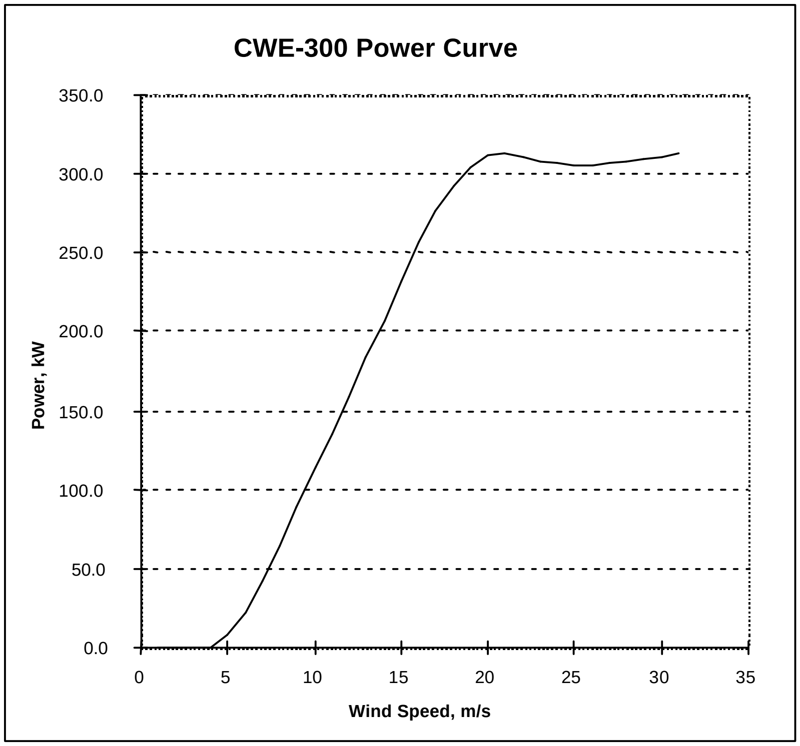

Figure 32. Power curve for run pitch angle 2.8-degree

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13. ABSTRACT *(Maximum 200 words)*
This report is a summary of activity on this subcontract during the period from September 1, 1997 through August 30, 1999. The contract entailed the engineering, component tests, system field tests, certification, and preparation for manufacturing the existing Cannon Wind Eagle 300-kW (CWE-300) wind turbine. The CWE 300 is a lightweight, flexible machine with a number of innovative design features that, relative to comparable rigid-hub machines, promises to contribute to reduced capital, installation, and maintenance costs. The architecture of the CWE-300 evolved from earlier wind turbine models developed over several decades. The current design retains many of the desirable features of earlier machines, addresses problems exhibited by those machines, and incorporates further innovative design features.

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